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Final Report

OPTIMAL DESIGN OF FREEWAY INCIDENT RESPONSE SYSTEMS

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May 2000

Indiana
Department
of Transportation

Purdue
University

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16. Abstract

Several states have introduced service patrol programs to curb the growing adverse impacts of freeway incidents. An efficient patrol program configuration design is needed to ensure appropriate resource allocation. This research seeks to devise a scheme for determining optimally such system characteristics as hours of operation, fleet and crew sizes, dispatching policies, areas of operation, and routing patterns, so that the efficacy of the program is maximized. The interaction of randomly occurring incidents with time-varying traffic adds to the complexity of the problem. The problem is solved using dynamic simulation approaches combined with optimization techniques to incorporate the non-linear impact of incidents on traffic. Simulation approaches are utilized to replicate the operation of response services, whereas optimization techniques are incorporated to select cost-effective system parameters. A generalized framework is developed that can be used to design new freeway patrol programs and improve existing ones. As an example application of the proposed tool, the case of the Hoosier Helper Program in northwest Indiana, is studied in detail.

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IMPLEMENTATION REPORT

As a low-cost approach to incident management, freeway service patrol programs have gained wide popularity. Although there are many such programs in different parts of the country, not much research has taken place in designing such programs systematically. An efficient design of patrol program configurations is needed to ensure appropriate resource allocation. This research seeks to devise a methodology for determining optimally such system parameters as hours of operation, fleet sizes, dispatching policies, areas of operation, and routing schemes so that the efficacy of the program is maximized.

This problem cannot be approached analytically, because of the interaction of randomly occurring incidents with time-varying traffic. The problem is therefore solved using dynamic simulation approaches combined with optimization techniques.

Simulation approaches are utilized to replicate the operations of response vehicles that move through the traffic on freeways. The incident occurrence is simulated from incident generation model that uses non-homogeneous Poisson process. Aggregate route diversion models are used along with queuing models to capture the non-linear impact of incidents on traffic flow in the network. Performance measures such as travel intensity and delay in queue in the network are utilized to estimate the efficacy of the incident response program.

Optimization techniques are used to design new programs efficiently and improve existing programs by making intelligent decisions about system parameters. As all the system parameters are not commensurable and there is no analytical expression for system performance measures, traditional optimization techniques may not be used. While simulation models are utilized to estimate system performance measures, nested partitions method is used to partition feasible region systematically to adapt sampling. Sampling is concentrated in the subset that is considered most promising. The initial promising region is obtained using the idea of sample path optimization. A load balancing heuristic technique is used to come up with an initial good design. Subsequently, nested partitions method and simulation models are used iteratively to select cost-effective system parameters.

A generalized framework is developed that can be used to design new freeway patrol programs and improve existing ones. As an example application of the proposed tool, the case of Hoosier Helper program, operated by the Indiana Department of Transportation (INDOT) in northwest Indiana is studied in details. It is shown how the efficiency of the Hoosier Helper program can be improved by adopting a different deployment schedule and routing scheme. The scope of further improvement by implementing different dispatching policies as well as increasing fleet size is also discussed. The framework developed in this study is easily transferable. In order to use it for designing new program or improving the operations of the existing programs the incident data, traffic data, and the network geometry data for the study area have to be collected and the simulation models should be calibrated accordingly. The other data to be obtained are the dollar value of a vehicle-hour saved and the cost data that includes investment cost, overhead cost, maintenance cost, and employees' salaries and benefits. These data are needed to estimate the marginal benefit-cost ratio that would be used to find out the cost-effective fleet size. Once all these data are obtained simulation models can be used combined with load balancing algorithm and nested partitions method to determine the optimal configuration design of incident response systems. The framework may be used for designing the Hoosier Helper program in the Indianapolis area as well as for similar programs in other parts of the country.

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CHAPTER 1

INTRODUCTION

1.1 Background

Non-recurrent congestion caused by highway incidents is a major concern for transportation agencies and millions of road users in most metropolitan areas in the United States. Highway congestion represents a daily problem for commuters and truckers in all major metropolitan areas. The Federal Highway Administration (FHWA) reported that non-recurrent congestion, or congestion caused by traffic incidents, accounts for 60 percent of congestion induced delay (Grenzeback and Woodle, 1992). Moreover, highway incidents cause fatalities, physical injuries, and property damage. In 1997, approximately 42,000 people died in motor vehicle crashes (FHWA, 1998). If immediate medical assistance had been available, many of these lives would have been saved. In the search for a lower-cost approach to combat the effect of traffic incidents on freeway operation, several states have made freeway service patrols an increasingly popular choice in larger urban areas. Freeway service patrols function as a "low-tech" incident management program, providing incident detection, response, and clearance; moreover, based on the findings of service patrol evaluations in the literature, these programs can serve as a key component within any comprehensive incident management framework. It is considered that an efficient freeway service patrol substantially reduces incident duration time which, in turn, alleviates the delay attributed to non-recurrent, incident-related congestion and lowers the chance of secondary crashes. Furthermore, these programs create a sense of security for motorists in addition to improving public relations for the service's sponsor (Nowlin, 1994).

1.2 Scope for Research

The effectiveness of an incident response program largely depends on how efficiently it has been designed. The issues that naturally come up are as follows: what the number of response vehicles should be, how many of them should be deployed at a time, whether this number should vary with time, which area they should cover, and how the vehicle's beat should be designed. In addition, one would be interested to know whether a particular policy for making the decision regarding which incident to be responded to next has any advantage over other policies. Thus, the design parameters include fleet size, deployment schedule, area of operation, routing scheme, and dispatching policy. These parameters should be selected intelligently. Although there are many incident response programs in different parts of the country, not much research has been done in developing systematic design procedures of these programs. An efficient design of patrol program configurations is needed to ensure appropriate resource allocation. The present research seeks to devise a methodology for determining optimally such system parameters as fleet size, hours of operation, area of operation, dispatching policy, and routing scheme so that the efficacy of the program can be maximized.

1.3 Outline of the Study

The problem cannot be approached analytically because of the interaction of randomly occurring incidents with time-varying traffic. The problem is therefore solved using dynamic simulation approaches combined with optimization techniques. The term "dynamic" is used to describe the time-varying nature of various components of the system. It includes traffic volume, incident occurrence, queue formation and dissipation, and route diversion. As they are inter-related, any change in one component may result in changes in others. Consequently, all these components need to be updated continuously for the period of simulation run, which is done by dividing the whole simulation period into a number of very small intervals and updating these components at each interval.

Simulation approaches were utilized to replicate the operation of response vehicles that move through traffic on freeways. The incident occurrence was simulated from an incident generation model that used a non-homogeneous Poisson process. Aggregate route diversion models were used along with queuing models to capture the non-linear impact of incidents on traffic flow in the network. Total vehicle-hours in the network was used as the performance measure to estimate the efficacy of the incident response program.

Optimization techniques were used to design new programs efficiently and improve existing programs by making intelligent decisions about system parameters. As all the system parameters are not commensurable and there is no analytical expression for system performance measures, traditional optimization techniques could not be used.

While simulation models were utilized to estimate system performance measures, a nested partitions method was used to partition a feasible region systematically to adapt sampling. Sampling was concentrated in the subset that was considered most promising. The initial promising region was obtained using the idea of sample path optimization. A load balancing heuristic technique was used to come up with an initial good design. Subsequently, the nested partitions method and simulation models were used iteratively to select cost-effective system parameters.

A generalized framework is developed that can be used to design new freeway patrol programs and improve existing ones. As an example application of the proposed tool, the case of the Hoosier Helper program in northwest Indiana was studied in details.

1.4 Organization of the Report

The report includes six chapters. Chapter 2 presents the literature review. In addition to discussing the work done in the past, it also highlights the contribution made by the research. Chapter 3 discusses the details of simulation modeling that includes incident generation, traffic simulation, replication of incident response operation, and estimation of system performance measures. Chapter 4 presents the methodology adopted for optimal system configuration design. It describes the framework developed combining a load balancing algorithm, the nested partitions method, and simulation models. Chapter 5 summarizes the findings of the research. As an example application of the proposed methodology, the case of the Hoosier Helper program in northwest Indiana is presented. Finally, conclusions are given in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Incident management programs to alleviate congestion have gained extensive popularity within the framework of Intelligent Transportation Systems (ITS). Incident detection, response, and clearance are the three basic components of incident management. Incident detection is probably the most widely studied area in incident management. Over the years a broad variety of algorithms have been developed to detect incidents as quickly as possible. Some of these algorithms are the California algorithm (Payne and Tignor, 1978) based on the shock-wave theory; Bayesian algorithm (Levin and Krause, 1978); generalized likelihood ratio algorithm (Willsky et al., 1980); autoregressive integrated moving average algorithm (Ahmed and Cook, 1982); the McMaster algorithm (Persaud et al., 1990) based on the catastrophe theory; low pass filtering algorithm (Stephanedes and Chassiakos, 1991); artificial neural network algorithms (Ritchie and Cheu, 1993; Stephanedes and Liu, 1995); and fuzzy logic algorithms (Han and May, 1990; Chang and Wang, 1994). These algorithms are based on traffic stream data which are collected by loop detectors, sensors, and video cameras. However, these data collection facilities may not be available in many places where incidents cause problem. Service patrol programs may be the only solution as they find incidents while covering the patrol area. Even if automatic incident detection is possible, a service patrol program can play a major role in response and clearance operation.

Several states have adopted freeway service patrol programs to mitigate the adverse effect of incidents. Table 2.1 presents a list of selected freeway service patrols operating in different states (Dutta et al., 1997; Nowlin, 1994; Morris and Lee, 1994; Cuciti and Janson, 1995; Georgia DOT, 1996; Minnesota DOT, 1994; Texas DOT, 1997; Hawkins, 1993). Although a significant amount of research has been conducted to evaluate the effectiveness of the freeway patrol programs, not much effort has been made to develop a systematic framework that can be used to improve the efficiency of existing programs and design a new program optimally. The present research is intended to fill the gap in the current literature.

2.2 Scope for Contribution

Emergency response has been a popular area of study in the operations research community. The past research focused on determining optimal location of depots and assigning emergency response vehicles to these depots. A significant amount of research has been directed towards such facility location problems. One of the earlier studies is by Toregas et al. (1971), where a set covering problem was formulated to minimize the number of service stations. Another notable study is by Fitzsimmons (1973) where the deployment of ambulances was studied in order to minimize the mean response time. Monte Carlo simulation was used to obtain the conditional mean response time and an iterative search technique was used to find the optimal result. Some heuristic techniques were also proposed to solve facility location problems (Daskin, 1983). There are several other location specific applications (Plane and Hendrick, 1977; Schilling et al., 1979; and Eaton et al., 1985). The reliability of such a system was modeled by a number of researchers (Daskin, 1983; ReVelle and Hogan, 1989). Ball and Lin (1993) showed how to determine simultaneously the optimal location of depots and the optimal assignment of vehicles to each of these facilities. Each of these studies has its own merit. However, the case of incident response is different from other emergency services such as ambulance and fire trucks, because the incident response vehicles need to keep on patrolling in search of incidents when they are free, while ambulances and fire trucks wait in depots for calls when they are not responding to any emergency. Bertsimas and Ryzin (1993) studied the case of a mobile service unit in their paper on stochastic and dynamic vehicle routing. Their objective was to find a policy that would minimize the expected system time (wait plus service) of the demands. What is missing in all these studies is the interaction of response vehicles with traffic. They assumed the response vehicles to have some fixed average speed without considering the changing traffic conditions. More importantly, the objectives were to minimize either the waiting time or system time of incidents. As the primary goal of incident response is to reduce the adverse effect of incidents on traffic, the main objective in the present study would be to improve the system performance in terms of total vehicle-hours in the system rather than minimizing the waiting time or system time of incidents. In addition, fleet size was assumed to be pre-specified in all these studies. However, one important decision parameter in the present study is to find the optimal fleet size in a new patrol program and determine whether it would be cost-effective to increase or decrease the number of response vehicles in an existing program. Moreover, decisions regarding a deployment schedule are also to be made.

Liu (1997) developed freeway incident prediction models and proposed a set of guidelines for using these models so that the operation of an incident response program can be improved. There is an inherent assumption that a Traffic Operation Center (TOC) would have incident information and instruct response vehicles accordingly to attend an incident site or relocate and patrol on a particular route. The incident information would be known to the TOC, if an automatic incident detection system were already installed. However, most freeway patrol programs operate without automatic detection.

The purpose of the simulation model used by Liu (1997) was to show the effectiveness of incident prediction models in improving incident response operation. Although the guidelines were prescribed for using these models for a single vehicle as well as for multiple vehicles, results were presented only for the single vehicle case. The speed of the response vehicle was also assumed to be constant, irrespective of prevailing traffic conditions. Furthermore, the area of responsibility for each response vehicle was determined simply by dividing the workload equally among them. However, this does not guarantee the optimal assignment of area of responsibility. Other critical issues, such as optimal fleet size, hours of operation, and areas of operation, were not addressed in Liu's study (1997).

The study by Zografos et al. (1993) directly addressed the problem of designing freeway incident response programs. A detailed review is therefore presented here.

Zografos et al. (1993) used a framework combining optimization and simulation techniques to deploy incident response vehicles along a freeway corridor such that the incident delay would be within some acceptable limit. While simulation models were used to replicate operation of response vehicles and estimate delay due to an incident, optimization techniques were utilized to minimize the travel time of the response vehicles. However, no attempt was made to find how many vehicles should be deployed at different periods of the day. Moreover, the only dispatching policies considered were the first-come-first-served and nearest neighbor policies. The study also has some other limitations that need to be addressed.

Route diversion was not taken into account by Zografos et al. (1993). They considered only the traffic on freeway segments covered by response vehicles. However, as the adjacent streets are affected by route diversion from freeway, these streets are also to be included in the study area. In their model, the speed of the response unit was determined by the volume-capacity (v/c) ratio prevailing just before the incident occurrence. However, the effective v/c ratio, while the incident is active, is different than the v/c ratio before incident occurrence. The v/c ratio should be updated at each simulation interval and the speed should be adjusted accordingly. Average values based on type of incident were used for incident clearance time (on-site service time). Considering the variation involved in incident clearance, clearance times should be randomly generated from fitted distributions rather than average values. Another important difference of the earlier studies (Zografos et al., 1993; Nathanail and Zografos, 1995) from the present research was that they assumed that response vehicles work from fixed bases. If there are no incidents to be responded, the vehicles return to their respective bases. This assumption may be justified if there is an automatic incident detection system. However, in most current programs response vehicles take the responsibility of detecting incidents to which they are going to respond. Consequently, there needs to be a provision for routing response vehicles through time-varying traffic and for these vehicles to undertake the duties of incident detection as well as response. Next, while determining the area of responsibility of each response unit, a mixed integer programming formulation was used. However, a restrictive assumption was made as it was considered that the workload for each freeway segment was concentrated at its center point. The objective function was to minimize the travel time of the response vehicles. Ideally, the goal should be the improvement of the system performance measure, such as total vehicle-hours in the system, rather than minimizing the travel time of response vehicles as it does not guarantee the best assignment of areas of responsibility. In Zografos (1993), the travel time calculation for the response unit involved estimation of the average time needed to cover the distance between the base and the center point of the freeway segment. This does not account for the actual travel time, as the incident site may be anywhere on the freeway segment. Sometimes a response vehicle has to go directly from one incident site to another before returning to its base. This was also not considered in the estimation of travel time for the response vehicle. Although both simulation modeling and optimization techniques were used, no effort was made to optimize a system performance measure (such as delay) obtained from the simulation model. An optimization model was utilized to assign the areas of responsibility to a given fleet size in such a way that would minimize the travel time of response vehicles. The areas of responsibility obtained from the optimization model were used as input variables in the simulation model to estimate the average delay. If the estimated delay was above a threshold, the fleet size was increased by one. The procedure was repeated until the estimated delay was below the threshold. The simulation model was used only to make a decision about fleet size. It was not ensured that for a given fleet size the best possible areas of responsibility were found, as no effort was made to optimize the system performance measure obtained from the simulation model. In the present study, an attempt is made to overcome the limitations of the previous studies.

Table 2.1: Selected Freeway Service Patrol Programs in the United States

State	Location	Patrol Name (year started)	Ownership	Number of Vehicles	Hours of Operation	Benefit-Cost Ratio (year)
California	Los Angeles	Freeway Service Patrol (1991)	public	153 tow trucks	peak hours	11:1 (1994)
California	San Francisco Bay Area	Freeway Service Patrol (1992)	public	49 tow trucks	peak hours	N/A
California	Orange County	Freeway Service Patrol (1992)	public	12 tow trucks	peak hours	N/A
California	Sacramento	Freeway Service Patrol (1992)	public	6 tow trucks	peak hours	N/A
California	San Diego	Freeway Service Patrol (1993)	public	15 tow trucks	peak hours	N/A
Colorado	Denver	Mile-High Courtesy Patrol (1992)	public	4 tow trucks, 2 pick-up trucks	peak hours	10.5:1 to 16.9:1 (1993)
Georgia	Atlanta	Highway Emergency Response Operator (1996)	public	12 pick-up trucks	daytime hours	N/A
Illinois	Chicago	Emergency Traffic Patrol (1960)	public	3 heavy tow trucks, 36 tow trucks, 11 pick-up trucks	24 hours	17:1 (1990)
Maryland	Baltimore Area	Emergency Traffic Patrol (1989)	public	4 tow trucks	peak hours	N/A
Maryland	Washington Area	Emergency Traffic Patrol (1989)	public	4 tow trucks	peak hours	N/A
Michigan	Detroit	Courtesy Patrol Program (1994)	public / private	4 vans	peak hours	15:1 (1996)
Minnesota	Minneapolis	Highway Helper (1987)	public	7 pick-up trucks	daytime hours	2.3:1 (1994)
New Jersey	Morris, Essex, Bergen Counties	Emergency Service Patrol (1993)	public	8 vans	daytime hours	11:1 (N/A)
New York	New York Metropolitan Area	Highway Emergency Local Patrol (1994)	public	28 pick-up trucks	peak hours	26:1 (1996)
North Carolina	Charlotte, Winston-Salem, Greensboro, Haywood County	Motorist Assistance Patrol (1992)	public	8 pick-up trucks	daytime hours	7.6:1 (1993)
Texas	Houston	Motorist Assistance Program (1986)	public / private	2 pick-up trucks, 18 vans	daytime hours	7:1 to 36:1 (1991)
Texas	Houston	District 12 Service Patrol (1971)	public	1 pick-up truck	nighttime hours	2:1 (1976)
Texas	El Paso	Texas Courtesy Patrol (1993)	public	6 pick-up trucks	daytime hours	N/A
Texas	Dallas	Texas Courtesy Patrol (1987)	public	14 pick-up trucks	daytime hours	N/A
Texas	Fort Worth	Texas Courtesy Patrol (1973)	public	6 pick-up trucks	24 hours	N/A
Texas	San Antonio	Texas Courtesy Patrol (1978)	public	6 pick-up trucks	24 hours	N/A
Texas	Austin	Texas Courtesy Patrol (1997)	public	2 pick-up trucks	daytime hours	N/A
Washington	Seattle (2 floating bridges)	Incident Response Team (1990)	public	4 tow trucks	peak hours	N/A

CHAPTER 3

SIMULATION MODELING

3.1 Introduction

Simulation modeling was used to replicate the operation of incident response vehicles that are moving through freeway traffic. The incident occurrence was simulated from an incident generation model that used a non-homogeneous Poisson process. Aggregate route diversion models were used along with queueing models to capture the non-linear impact of incidents on traffic flow in the network. Total vehicle-hours in the network was used as the performance measure to estimate the effectiveness of the incident response program. The system parameters of an incident response program include beat design, hours of operation, area of operation, fleet size, and deployment schedule. As the system parameters are not commensurable and there is no analytical expression for system performance measures, traditional optimization techniques could not be used. A nested partitions method was used to optimize the performance of the system and a load balancing heuristic technique was used to formulate an initial good design to initiate the nested partitions method. The simulation model was used iteratively with the partitioning approach to select an optimal design so that the system parameters were most cost-effective.

An explicit traffic simulation model was developed in the present study that included route diversion. When the congestion level on a freeway is high, travelers may switch from the freeway to adjacent parallel arterial roads. While defining the boundary of the study area, these adjacent links should be included in the system under consideration, as they absorb the changes in dynamic traffic conditions on freeway. Hence, the system definition in the proposed simulation model included both the freeway segments the response vehicles patrol and the adjacent roads. The effectiveness of the patrol program was measured through direct system performance indicators such as total vehicle-hours in the system. The influence of different dispatching policies of response vehicles on the quality of service was also incorporated in the modeling process.

3.2 Need for Simulation Modeling

The occurrence of incidents is random in nature. They reduce the capacity of the road segment and hamper the smooth flow of traffic. If the impact is too adverse, travelers divert to alternative routes causing increased traffic volume on these routes. Thus, the congestion spills over from the freeway to the adjacent street network. Moreover, the impact of incidents on time-varying traffic is non-linear in nature and any analytical expression may not be suitable for impact evaluation. Simulation approach may be adopted to update traffic volume at desirable time intervals and replicate route diversion if it occurs. Thus, the impact of randomly occurring incidents on time-varying traffic may be evaluated comprehensively using a simulation model.

The incident response operation is also complex. Response vehicles patrol assigned freeway segments and look for incidents according to a deployment schedule.

Upon detection of an incident, a vehicle reaches the incident location and provides assistance. If it is a major incident, arrangements are made for ambulance, towing, and other necessary services. After the clearance of an incident, the response vehicle resumes its normal patrol operations. Sometimes incidents are detected using automated detection technologies and patrol vehicles are directed to the incident location from a Traffic Operations Center (TOC). After the scheduled period of patrol is over, response vehicles return to the depot and new vehicles take over their duties. Freeway patrol vehicles try to clear incidents on the freeway as quickly as possible so that the adverse effect of incidents is minimal. The operational parameters of the patrol program, such as fleet size, hours of operations, location and size of patrol area, influence how quickly the incidents can be removed. In order to evaluate the effectiveness of the freeway service patrol program, its operation needs to be reproduced and its contribution in reducing the impact of incidents on traffic should be measured through a simulation model.

Although there are a number of commercially available software packages including INTRAS, FREESIM, and INTEGRATION for freeway traffic simulation, none of them has a provision for replicating the operation of a freeway service patrol program. Therefore, a new simulation model had to be developed that could explicitly replicate the operation of patrol vehicles through prevailing freeway traffic conditions. Special attention was given to computational efficiency as the simulation tool was to be subsequently used to estimate the effectiveness of the service patrol program for a wide range of system parameters.

3.3 Description of the Simulation Model

It should be noted that incident response operation is influenced by traffic flow as incident response vehicles have to move through traffic varying with time, and their speed is dependent on the volume level of the road links they are travelling on. On the other hand, incidents affect traffic flow by reducing link capacity, and the degree of this adverse impact depends on incident duration to a great extent. The response vehicles reduce incident duration by responding to incidents as soon as possible. Thus, traffic flow, incident duration, and response operation are inter-dependent, as shown in Figure 3.1.

A mesoscopic approach was adopted in the simulation model developed for replicating the freeway service patrol operation. While the traffic flow was modeled in a macroscopic level rather than keeping track of individual vehicles in the traffic stream, the movement of the response vehicles was microscopically tracked. By aggregated modeling of corridor traffic, the influence of traffic on the movement of response vehicles could be sufficiently captured saving a large amount of computational time.

The simulation modeling involved replication of incident occurrence, traffic flow in different links varying with time, response vehicle movement in their patrol areas and incident clearance, and evaluation of the effectiveness of the response operation. There are four major modules in the proposed simulation model, as shown in Figure 3.2. These are: a) Incident Generation, b) Traffic Simulation, c) Simulation of Incident Response, and d) Estimation of System Performance Measures.

3.3.1 Incident Generation

Incidents occur as random events. The random nature of incident occurrence can be replicated using the incident generation module. The number of incidents occurring in a day is a non-negative integer. Counting distribution like Poisson distribution is suitable for a random variable whose outcomes are non-negative integers (Law and Kelton, 1991). The rate of incident occurrence varies at different times of the day. Hence, time-varying non-homogeneous Poisson distribution was used to model incident generation. There are other temporal effects. Different seasons of the year and days of the week influence the rate of occurrence. In the proposed simulation model four seasons were considered: winter, spring, summer, and fall. There is also a provision of generating incidents occurring on a weekday and on a weekend-day separately for each season. For each different scenario, the rates of incident occurrence at different hours of the day need to be provided as input data.

The schematic diagram of the incident generation module is presented in Figure 3.3. The distribution of incidents in terms of link of occurrence is to be obtained from the field data. The longitudinal location of incidents on a given link can be assumed uniformly distributed along the entire link length. The lateral position of the incident (if it is on a shoulder or on a lane) can also be determined from a probability distribution.

Incidents were broadly categorized into four major types: disablement, abandoned vehicles, debris, and crashes. Distribution of type of incidents for the study area is to be determined and entered as input data.

The degree of difficulty in clearing incidents largely depends on incident type and incident position. For example, in-lane crashes would probably take more time to be cleared than debris on a shoulder. Distributions like gamma, exponential, log-normal, and Weibull are suitable for fitting incident clearance time distributions. Depending on the type and position of incidents, incident clearance time can be generated from fitted distributions.

3.3.2 Traffic Simulation

Traffic simulation is an essential part of the proposed evaluation and design tool. The effectiveness of a freeway service patrol program depends on how much it can reduce the adverse effect of incidents on traffic. The flowchart of traffic simulation is shown in Figure 3.4.

3.3.2.1 Capacity and Speed Change

In order to capture the time-varying nature of traffic, link volumes at each hour of the day are entered as input data of the simulation model. Other data such as the link capacity and the number of lanes in each direction are also needed. Incidents obstruct the smooth flow of traffic by reducing the link capacity. The extent of capacity reduction depends on the type and lateral location of incidents as well as the number of lanes in each direction. The capacity reduction values obtained from a study by Sullivan (1997) were used in the present model. These values are presented in Table 3.1. Due to capacity reduction, the average speed on the link is also reduced. At each simulation interval the volume-capacity (v/c) ratio on each link is estimated and the average speed on the corresponding link is modified accordingly. The Bureau of Public Roads (BPR) link performance functions, reported in Mannering et al. (1990), were used for speed calculation in the simulation model. A simulation interval of 10 seconds was used in the study. However, there is flexibility of varying the size of the simulation interval.

3.3.2.2 Queueing and Route Diversion

Incidents reduce roadway capacity. If the reduced capacity is less than the traffic demand, a queue starts to form. At each simulation interval, it is checked whether queue is formed; and if a queue is already formed, the queue length is determined according to the traffic demand. When the volume-capacity ratio on a freeway segment is beyond a threshold, vehicles on the freeway start to divert to alternative routes at the nearest exit. As a result, volume levels in some freeway segments and adjacent arterials change. After the incident is cleared and original capacity is restored, the queue begins to dissipate. After the queue is dissipated, traffic volumes on affected links are readjusted and original traffic flow levels are restored.

Travelers on the freeway divert to alternate routes when they perceive that they can save travel time by using alternative routes. Often such perception is triggered by the stop-and-go condition on the freeway. If no highway advisory system exists, which is the case for many response programs, travelers rely on their perception about the congestion level to make decision regarding route diversion. Since v/c ratio is a good indicator of the level of congestion, it was used to model route diversion. A v/c ratio of 1.3 was used to represent this stop-and-go condition on the freeway and subsequently used as the threshold value for initiating route diversion. A v/c ratio of 2.0 represents jam density. Hence, it was assumed that all the vehicles would divert from the freeway at the link v/c ratio of 2.0 or above. A linear interpolation was used to calculate the percentage of traffic diverting from the freeway when the v/c ratio is between 1.3 and 2.0. The diverted traffic was distributed among alternative routes in proportion to the capacity of the entry links of these routes. Diverted traffic was routed back to the freeway after bypassing the congested link or links.

3.3.2.3 Volume Change

When traffic diverts from the freeway, the volume level on the freeway goes down and volumes on parallel routes go up. However, the change in volume level is not observed simultaneously on all the links. After bypassing the incident, diverted traffic would like to come back to the freeway. It was assumed that diverted traffic would be able to return to the freeway within two interchanges following the incident site. The road segments located further from the incident site experience the change in volume level later than those located nearer to the incident site. After the incident is cleared and the queue is dissipated (if formed), volume levels on affected freeway segments and alternative routes return to their original values. Again the volume levels on road segments located further from the incident site return to their original values later than those on segments located nearer to the incident site. There is a time lag for each of the links that determines how long after the incident occurrence the effect would be observed on a link or how long after the incident clearance the effect on it would disappear. These values depend on the location of the links relative to the incident site and may be estimated from the average travel time from the entry point of the link on which the incident is located to the entry point of the affected link. At each simulation interval, it is checked whether the incident and queue (if any) are present and the volume level on each segment is adjusted accordingly. Apart from route diversion, the volume levels are also changed as per the regular hourly variation in traffic demand.

3.3.3 Simulation of Incident Response Operation

The schematic diagram for incident response operations is presented in Figure 3.5. While the response vehicles are off-duty, they stay at a depot. Following a schedule, these vehicles are deployed in their respective patrol areas. The patrol routes and the deployment schedule can be modified by changing the input data files. Response vehicles patrol the assigned freeway segments and look for incidents. In addition to visual detection by response vehicles, sometimes incidents are detected using automated detection technologies. There are provisions for both types of detection in the incident detection sub-module of the simulation model.

3.3.3.1 Movement of Incident Response Vehicles

After detecting an incident, a response vehicle tries to reach the incident location. If an incident is detected on the other side of the freeway, the response vehicle makes a turn-around from the nearest exit ahead, if such a policy is allowed. The position of the response vehicle is updated in each simulation interval according to the link speed in that interval on which it is traveling. On a very congested freeway segment, it may travel on the shoulder to reach the incident quickly, if the geometry permits. If the response vehicle is currently attending an incident, the new incident waits to be served later. It was assumed that alternative arrangements would be made if the new incident had to wait for a long time. On the basis of the experiences from the Hoosier Helper freeway patrol program in northwest Indiana, it was decided that travelers would make their own arrangements for assistance rather than relying on the freeway patrol if they wait more than 30 minutes on the average. This waiting period may vary from location to location and may be adjusted by consulting local transportation agencies. When there is more than one incident waiting to be cleared by a response vehicle, a priority list can be made as per the severity of incidents; and the response vehicle is sent to the incident location following a particular dispatching policy. The severity of an incident depends on the type and lateral location of the incident. For example, an in-lane crash is more severe than a disablement on a shoulder and can be served earlier. The priority list used in the present study is shown in Table 3.2.

3.3.3.2 Dispatching Policies

When incidents are detected visually by patrol vehicles, the range of detection is limited to the sight distance of the vehicles, and incident information in the rest of the area is not available. The following dispatching policies were considered for a visual detection system:

- Policy A : First Reached First Served without Crossing to the Other Side

According to this policy, the vehicle always follows its pre-specified patrol route. Even if it detects an incident on the other side, it does not turn back before reaching its pre-specified exit for turn-around. It clears incidents in the order it reaches them in its patrol route.

- Policy B : First Reached First Served with Crossing to the Other Side

This is a modified version of policy A. Unlike policy A, the response vehicle turns back from the nearest exit ahead if it detects an incident on the other direction of travel.

- Policy C : Most Severe First

According to this policy, the most severe incident among all the incidents detected is served first. The severity level can be determined according to the type and location of incidents, as presented in Table 3.2. In order to clear the major incident quickly, this policy allows turning around, as well as crossing a relatively less severe incident without assisting it.

In all of three policies, the response vehicle resumes its normal patrol operation after clearing all the incidents waiting for response.

When automated detection technologies are used, incident information in the entire patrol area is available in a Traffic Operations Center (TOC). Depending on traffic conditions, approximate time required by different response vehicles to reach different incident locations can be estimated at the TOC. This information can then be used to modify dispatching policies.

- Policy D : Most Severe with Minimum Time to Respond First with Vehicle Patrolling

According to this policy, the most severe incident is served first. In case of a tie in terms of severity, the one that takes less time to be reached is attended first. The response vehicle resumes its normal patrol operations after clearing the incident.

- Policy E : Most Severe with Minimum Time to Respond First with Vehicle Waiting on Shoulder

The incident to be attended first is determined in the same way as in policy D. However, the major difference in this policy is that response vehicles do not patrol along the freeway, rather they wait on the shoulder near the center of their assigned service areas. The incidents are detected by an automated system. Upon detection of incidents, response vehicles are directed from the TOC regarding which incident is to be responded immediately. After clearing incidents, a response vehicle returns to its original location on the shoulder.

When a vehicle's scheduled time of operation is over, it returns to the depot from its patrol area and vehicles with a new crew take over the response operation duties.

3.3.4 Estimation of System Performance Measure

The schematic diagram for the estimation of a system performance measure is presented in Figure 3.6. In the present simulation model total vehicle-hours in the system was used as the performance measure. Total vehicle-hours in the system includes time spent by all the vehicles in the study area while traveling as well as while waiting in a queue. This parameter can also be referred to as system-wide travel time. In the absence of a freeway patrol program, it would take more time to clear incidents. As a result, total vehicle-hours in the study area would be higher. The reduction in total vehicle-hours due to the freeway service patrol program can be perceived as its effectiveness.

At the beginning of simulation, total vehicle-hours in the system is initialized to zero for all the links in the study area. At the end of each simulation interval, performance statistics are collected. For each link, vehicle-hours in the current interval is calculated and it is added to the previous value to obtain the cumulative vehicle-hours on that link. It is also checked at the end of each simulation interval whether there is any queue present on that link. If a queue is present, the queue length and the delay in the queue are calculated and added to the total vehicle-hours on that link. At the end of each simulation interval, the simulation clock is moved. After the desired simulation time is over, the cumulative vehicle-hours for all the links are added to obtain total vehicle-hours in the system.

3.4 Case Study : Hoosier Helper Program

The simulation model, developed in the present study, is a generalized tool that can be used to replicate the operation of a freeway service patrol and measure its effectiveness. As an example application of the proposed simulation model, the case of the Hoosier Helper patrol program in northwest Indiana is presented. The Hoosier Helper program is a roving freeway service patrol program that started on August 30, 1991. The program, supported by the Indiana Department of Transportation (INDOT), deploys at least two vehicles in service 24 hours a day, seven days a week. It was expanded to 24-hour operation on Memorial Day weekend, 1996. Prior to that, the program provided motorist assistance between the hours of 6:00 AM and 8:30 PM. Hoosier Helper crews regularly patrol a sixteen-mile stretch of the six-lane Interstate 80-94 freeway near Gary, commonly known as the Borman Expressway, seeking and responding to incidents. The Borman Expressway runs from the Indiana-Illinois border to the Interstate 90 interchange. In addition, during peak travel periods, the program's crews cover a portion of the four-lane Interstate 65 freeway from U.S. Highway 30 in Merrillville to U.S. Highway 20 in Gary, close to the Interstate 90 interchange. The map of the patrol area is presented in Figure 3.7. Currently, three response vehicles are deployed in the peak period (from 6:00 AM to 10:00 AM and from 3:00 PM to 7:00 PM). During the off-peak period (from 10:00 AM to 3:00 PM and from 7:00 PM to 10:00 PM) two response vehicles patrol the Borman Expressway. I-65 is not covered during this period. Also during the night-time operation (from 10:00 PM to 6:00 AM) two response vehicles are deployed and I-65 is not covered. Examples of motorist assists, provided free of charge by the program, include supplying fuel, changing flat tires, calling private tow truck operators, and furnishing support at crash sites.

3.4.1 Validation of Incident Generation Model

Hoosier Helper patrolmen maintain a daily activity log documenting all assists made. At the conclusion of an assist, a patrolman will record the following information regarding the incident: Hoosier Helper arrival time, road, direction of travel, mile marker, state and license plate number of vehicle assisted, type of vehicle assisted, lateral location of incident, services rendered, and Hoosier Helper departure time. The incident information based on records of motorist assists, collected by INDOT during the period from August 1991 to December 1996, was used to obtain distribution of incidents by time of year and type of incident. The average hourly incident rate was used to generate incidents in each hour. The Poisson distribution, where the mean was the average hourly incident rate, was used to determine the number of incidents occurring in each hour, as it was considered well suited to generate non-negative integers. Statistical tests were conducted to determine the goodness of fit. As an example, the plot of observed and theoretical (calculated based on fitted Poisson distribution) frequencies of incidents in a particular hour (8AM-9AM) on fall weekdays of 1996 is presented in Figure 3.8. The goodness of fit was found significant at 99% confidence level (test statistic = 10.90, critical value = 15.09). For each hour, probability values for the occurrence of different types of incidents were calculated from the collected incident data. A random number was generated from a uniform distribution with a range of 0 to 1 that was subsequently used to determine the incident type depending on the cumulative probability values for the occurrence of different types of incidents. Hourly incident rates and probabilities of occurrence of different types of incidents in each hour were used in the simulation model. These data were aggregated to obtain daily incident rates and percentages of different types of incidents, as shown in Table 3.3, for the sake of the brevity of presentation. Appropriate distributions for incident clearance times were also generated on a disaggregated basis using the same database. Table 3.4 presents a statistical summary of clearance times by type and location. Several distributions were fitted depending on type, location, and time of occurrence of incident, as summarized in Table 3.5.

The incident generation model was validated using the chi-square test by comparing simulated and observed incidents. Simulated and observed incidents occurring at different hours for weekdays as well as weekends in each of the four different seasons were compared, and the match between simulated and observed incidents was found statistically significant for all scenarios. As an example, simulated and observed incidents on summer weekdays were plotted in Figure 3.9. It can be observed that the pattern of simulated incidents closely resembled that of observed incidents in the study area. The resemblance was found significant at 99% confidence level (test statistic = 33.2, critical value = 41.64).

3.4.2 Validation of Traffic Simulation Model

Information on the deployment schedule and routing of the Hoosier Helper program was collected. Traffic volume and link geometry data for the study network were obtained from INDOT. For each link, the hourly volume, length, capacity, and number of lanes were entered as input data. Currently, patrol vehicles detect incidents visually and respond following the dispatching policy B, as mentioned in Section 3.3.3.2. The automated detection system is in the process of being installed. Hence, the possibility of adopting other policies was explored in the present study.

The traffic simulation model was validated by comparing the volume and speed data obtained from the simulation model with the field data using the chi-square test. For example, the hourly volume data obtained from the simulation model for two specific links on the Borman Expressway and I-65 were plotted against the hourly volume data collected by INDOT on these links. It can be seen from Figures 3.10 and 3.11 that the hourly volume data obtained from the simulation model were close to the field data. The match was found significant at 99% confidence level (test statistic for Borman data = 0.1129, test statistic for I-65 data = 0.2156, critical value = 41.64). Similarly, the average speed data obtained from the simulation model were plotted against the speed data collected on a segment of the Borman Expressway as shown in Figure 3.12. It can be observed that the simulated data and the field data had much similarity that was found significant at 99% confidence level (test statistic = 6.45, critical value = 41.64). While the overall matching was very close, there were differences during certain hours of the day. For example, the simulated speed was higher than the observed speed during the night, while the reverse was observed during the day, especially in the morning and afternoon peak periods. The apparent discrepancy can be explained by the fact that while the percentage of truck traffic on the Borman Expressway is high compared to other freeways, the percentage is much higher during the night hours. As the truck speed limit is 5 mph less than that for automobiles, a high percentage of trucks would make the observed speed values less than the simulated data, because the trucks were not separately considered in the simulation.

3.4.3 Diagnostic Tests for Simulation of Incident Response

The input data for the proposed model were customized to simulate the operation of the Hoosier Helper program. To test how well the incident response system was being represented, the simulated incident clearance time was compared with the clearance time of all types of incidents on the Borman Expressway and I-65, as recorded in the Hoosier Helper logbook during the period from August 1991 to December 1996. As shown in Figure 3.13, there was a close resemblance between the simulated data and field data on the clearance time at 99% confidence level (test statistic = 2.07, critical value = 20.09). In addition, a set of diagnostics was utilized to do consistency checks. For example, it was tested whether the response vehicle was taking a reasonable amount of time to cover its patrol area. The time to complete a loop as obtained from the simulation model was compared with the sum of average link travel times for all the links on the loop. It was also checked whether any of the links register a negative volume at any point in time. A negative value would indicate a potential problem in the volume-updating module. Another test was made to see if a response vehicle was returning to its depot on time after its scheduled period of operation. The implementation of each of the five dispatching policies was verified by introducing incidents of different severity levels at various locations and checking the relative order in which they were responded. The queue formation and dissipation, as well as route diversion, were also studied by introducing severe incidents during the peak hours and taking snap shots of hourly volume, speed, and queue length at different points of time.

3.4.4 Performance Measure

After the simulation model was validated and diagnostic tests were performed, total vehicle-hours in the system was estimated with and without the Hoosier Helper response vehicles operating. The savings in total vehicle-hours in the system due to the freeway patrol program were used as the measure of effectiveness of the program.

3.5 Chapter Conclusions

In this chapter a simulation model was presented that can be used to measure the effectiveness of a freeway service patrol program. Even if one does not have the flexibility of changing existing resource levels for a patrol program, possibilities of further improvement under different deployment schedules, beat designs, and dispatching policies may be explored. The primary input data needed to run the simulation model include network data, traffic data, incident data, and patrol program data containing information regarding deployment schedule and routing. The proposed model runs relatively fast. For example, in a Sun (Ultra Sparc 1) Workstation it took 50 minutes on the average to simulate the operation of the Hoosier Helper program for 20 days on a study network with 38 nodes and 120 links.

The performance of a freeway patrol program can be improved by changing system parameters such as fleet size, hours of operations, area of operation, routing schemes, and dispatching policies. A systematic procedure can be developed that would optimally design a freeway patrol program using the results from the proposed simulation model. A detailed description of this procedure is presented in the following chapters.

Table 3.1: Percent Roadway Capacity Remaining for Different Incident Characteristics

Incident Type	Lateral Location of Incident	Number of Lanes	
		2 Lanes in Each Direction	3 Lanes in Each Direction
Crashes and Debris	Shoulder	81	83
	1 Lane Blocked	39	53
All Other Incident Types	Shoulder	84	90
	1 Lane Blocked	42	57

Table 3.2: Priority Ranking of Incidents According to Severity

Incident Type	Lateral Location of Incident	Priority Ranking
Crashes and Debris	Lane	1
Abandoned Vehicles and Disablement	Lane	2
Crashes and Debris	Shoulder	3
Abandoned Vehicles and Disablement	Shoulder	4

Note: - Incident with priority ranking one should be served first

Table 3.3: Distribution of Hoosier Helper Assisted Incidents by Time of Year and Type of Incident

Location	Season / Day of Week	Average Number of Incidents Per Day	Percent Disablement	Percent Abandoned Vehicles	Percent Debris	Percent Crashes
Borman Expressway	Summer / Weekday	42.2	70.7	14.4	7.8	7.1
	Summer / Weekend	31.2	75.2	13.7	3.7	7.4
	Fall / Weekday	37.1	66.0	19.8	6.5	7.7
	Fall / Weekend	33.9	73.2	18.1	4.9	3.8
	Winter / Weekday	32.4	68.4	18.4	4.0	9.2
	Winter / Weekend	34.1	65.0	14.9	4.6	15.5
	Total	36.9	69.6	16.8	6.1	7.5
Interstate 65	Summer / Weekday	6.9	70.8	16.9	4.0	8.3
	Summer / Weekend	3.8	66.3	22.8	4.0	6.9
	Fall / Weekday	4.1	67.8	20.2	2.6	9.4
	Fall / Weekend	2.9	74.7	13.3	0	12.0
	Winter / Weekday	4.1	66.7	20.0	0	13.3
	Winter / Weekend	3.6	68.7	18.8	3.1	9.4
	Total	4.7	69.4	18.4	3.0	9.2

Note: - Incident rate classification was based on 8,913 observations
- Incident type classification was based on 8,814 observations

Table 3.4: Clearance Time of Incidents Assisted by the Hoosier Helper Program

Incident Type	Incident Location			
	Lane		Shoulder	
	Mean	Standard Deviation	Mean	Standard Deviation
Disablement	13.85 (*179*)	19.16	12.11 (*5523*)	15.75
Abandoned Vehicles	3.19 (*52*)	2.35	3.10 (*1339*)	4.53
Debris	4.35 (*446*)	9.09	6.22 (*12*)	16.43
Crashes	34.42 (*254*)	30.98	24.84 (*315*)	29.01

Note: - All mean and standard deviation values are in minutes
- The number of observations per category is given in parentheses

Table 3.5: Fitted Distributions for Clearance Time of Incidents Assisted by the Hoosier Helper Program

Type of Incident	Location of Incident	Time of Occurrence	Fitted Distribution		
			Type	Parameters	P-value
Crash	Lane	6AM -9AM	Exponential	Shift Parameter=15 Lambda=31.2	>0.15
Crash	Lane	9AM -3PM	Weibull	Shift Parameter=4.5 Alpha=1.29 Beta=30.2	<0.005
Crash	Lane	3PM -6PM	Exponential	Shift Parameter=4.5 Lambda=13.7	0.0562
Crash	Lane	6PM -8.30PM	Weibull	Shift Parameter=0.5 Alpha=1.27 Beta=33.6	<0.005
Crash	Lane	8.30PM -11PM	Uniform	Shift Parameter=0 Alpha=28 Beta=130	>0.15
Crash	Lane	11PM -6AM	Weibull	Shift Parameter=18 Alpha=0.758 Beta=54.5	>0.15
Crash	Shoulder	6AM -9AM	Weibull	Shift Parameter=2 Alpha=0.84 Beta=31.5	>0.15
Crash	Shoulder	9AM -3PM	Exponential	Shift Parameter=2 Lambda=17.7	>0.15
Crash	Shoulder	3PM -6PM	Weibull	Shift Parameter=1.5 Alpha=0.936 Beta=12.8	0.0334
Crash	Shoulder	6PM -8.30PM	Weibull	Shift Parameter=0.5 Alpha=0.97 Beta=13.9	0.143
Crash	Shoulder	8.30PM -11PM	Uniform	Shift Parameter=0 Alpha=1.5 Beta=90.5	0.121
Crash	Shoulder	11PM -6AM	Uniform	Shift Parameter=0 Alpha=1.5 Beta=80.5	0.0765

Table 3.5, continued

Type of Incident	Location of Incident	Time of Occurrence	Fitted Distribution		
			Type	Parameters	P-value
Abandoned Vehicle	Lane	6AM -9AM	Gamma	Shift Parameter=0.5 Alpha=2.37 Beta=1.11	<0.005
Abandoned Vehicle	Lane	9AM -3PM	Gamma	Shift Parameter=0.5 Alpha=1.8 Beta=1.59	<0.005
Abandoned Vehicle	Lane	3PM -6PM	Weibull	Shift Parameter=1.5 Alpha=0.848 Beta=2.01	<0.005
Abandoned Vehicle	Lane	6PM -8.30PM	Weibull	Shift Parameter=1.5 Alpha=0.796 Beta=4.67	<0.005
Abandoned Vehicle	Lane	8.30PM -11PM	Exponential	Shift Parameter=0.5 Lambda=5.72	<0.005
Abandoned Vehicle	Lane	11PM -6AM	Weibull	Shift Parameter=1.5 Alpha=4.13 Beta=3.32	<0.005
Abandoned Vehicle	Shoulder	6AM -9AM	Gamma	Shift Parameter=0.5 Alpha=3.11 Beta=0.704	<0.005
Abandoned Vehicle	Shoulder	9AM -3PM	Gamma	Shift Parameter=0.5 Alpha=1.66 Beta=1.57	<0.005
Abandoned Vehicle	Shoulder	3PM -6PM	Gamma	Shift Parameter=0.5 Alpha=2.11 Beta=0.94	<0.005
Abandoned Vehicle	Shoulder	6PM -8.30PM	Gamma	Shift Parameter=0.5 Alpha=1.51 Beta=1.81	<0.005
Abandoned Vehicle	Shoulder	8.30PM -11PM	Gamma	Shift Parameter=0.5 Alpha=3.55 Beta=0.788	<0.005
Abandoned Vehicle	Shoulder	11PM -6AM	Gamma	Shift Parameter=0.999 Alpha=1.6 Beta=1.9	<0.005

Table 3.5, continued

Type of Incident	Location of Incident	Time of Occurrence	Fitted Distribution		
			Type	Parameters	P-value
Debris	Lane	6AM -9AM	Exponential	Shift Parameter=0.5 Lambda=4.45	<0.005
Debris	Lane	9AM -3PM	Gamma	Shift Parameter=0.5 Alpha=1.9 Beta=1.49	<0.005
Debris	Lane	3PM -6PM	Gamma	Shift Parameter=0.5 Alpha=2.52 Beta=1.22	0.0337
Debris	Lane	6PM -8.30PM	Exponential	Shift Parameter=0.5 Lambda=5.26	<0.005
Debris	Lane	8.30PM -11PM	Weibull	Shift Parameter=0.5 Alpha=0.338 Beta=4.52	>0.15
Debris	Lane	11PM -6AM	Weibull	Shift Parameter=1.5 Alpha=1.65 Beta=5.02	<0.005
Debris	Shoulder	6AM -9AM	Gamma	Shift Parameter=0.5 Alpha=1.09 Beta=4.14	>0.15
Debris	Shoulder	9AM -3PM	Gamma	Shift Parameter=0.5 Alpha=1.15 Beta=4.14	0.0215
Debris	Shoulder	3PM -6PM	Exponential	Shift Parameter=0.5 Lambda=3.98	0.0479
Debris	Shoulder	6PM -8.30PM	Weibull	Shift Parameter=0.5 Alpha=0.761 Beta=5.74	0.0264
Debris	Shoulder	8.30PM -11PM	Gamma	Shift Parameter=0.5 Alpha=1.16 Beta=4.09	0.0052
Debris	Shoulder	11PM -6AM	Exponential	Shift Parameter=0.5 Lambda=4.13	<0.005

Table 3.5, continued

Type of Incident	Location of Incident	Time of Occurrence	Fitted Distribution		
			Type	Parameters	P-value
Disable-ment	Lane	6AM -9AM	Weibull	Shift Parameter=0.5 Alpha=0.857 Beta=11.6	>0.15
Disable-ment	Lane	9AM -3PM	Weibull	Shift Parameter=0.5 Alpha=0.888 Beta=16.4	>0.15
Disable-ment	Lane	3PM -6PM	Weibull	Shift Parameter=0.5 Alpha=0.77 Beta=9.37	0.0354
Disable-ment	Lane	6PM -8.30PM	Weibull	Shift Parameter=0.5 Alpha=0.827 Beta=10.8	>0.15
Disable-ment	Lane	8.30PM -11PM	Weibull	Shift Parameter=2 Alpha=0.317 Beta=3.76	>0.15
Disable-ment	Lane	11PM -6AM	Gamma	Shift Parameter=1.5 Alpha=1.05 Beta=10.7	<0.005
Disable-ment	Shoulder	6AM -9AM	Weibull	Shift Parameter=0.5 Alpha=0.916 Beta=9.91	<0.005
Disable-ment	Shoulder	9AM -3PM	Exponential	Shift Parameter=0.999 Lambda=10.5	<0.005
Disable-ment	Shoulder	3PM -6PM	Exponential	Shift Parameter=0.999 Lambda=10.6	<0.005
Disable-ment	Shoulder	6PM -8.30PM	Exponential	Shift Parameter=0.999 Lambda=11.5	0.0101
Disable-ment	Shoulder	8.30PM -11PM	Exponential	Shift Parameter=0.999 Lambda=12.4	0.0099
Disable-ment	Shoulder	11PM -6AM	Exponential	Shift Parameter=0.999 Lambda=13.8	<0.005

Table 3.5, continued

Note:

- Shift parameter is added to the clearance time generated from fitted distributions.
- P-value indicates the goodness of fit. Lower the p-value, higher is the goodness of fit.
- The probability density functions (f(x)) of different distributions are given below:

Exponential: $f(x) = \frac{1}{\lambda} e^{-x/\lambda}$

Gamma: $f(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{(\alpha-1)} e^{-(x/\beta)}$

Uniform: $f(x) = \frac{1}{\beta - \alpha}$

Weibull: $f(x) = \beta\alpha x^{(\alpha-1)} e^{-\beta x^{\alpha}}$

where lambda: λ, alpha: α, beta: β, gamma function: Γ.

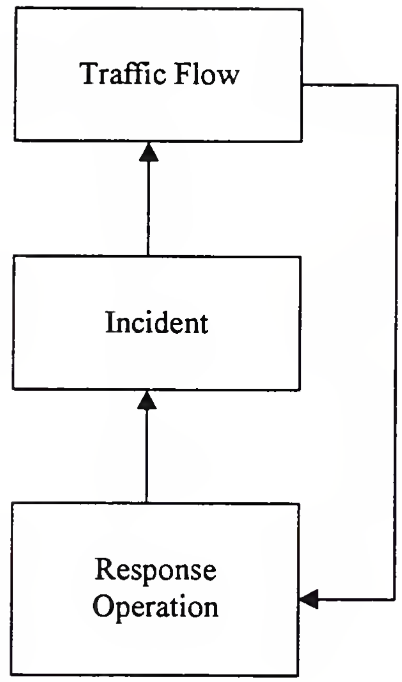


Figure 3.1: Relationship among Traffic Flow, Incident, and Response Operation

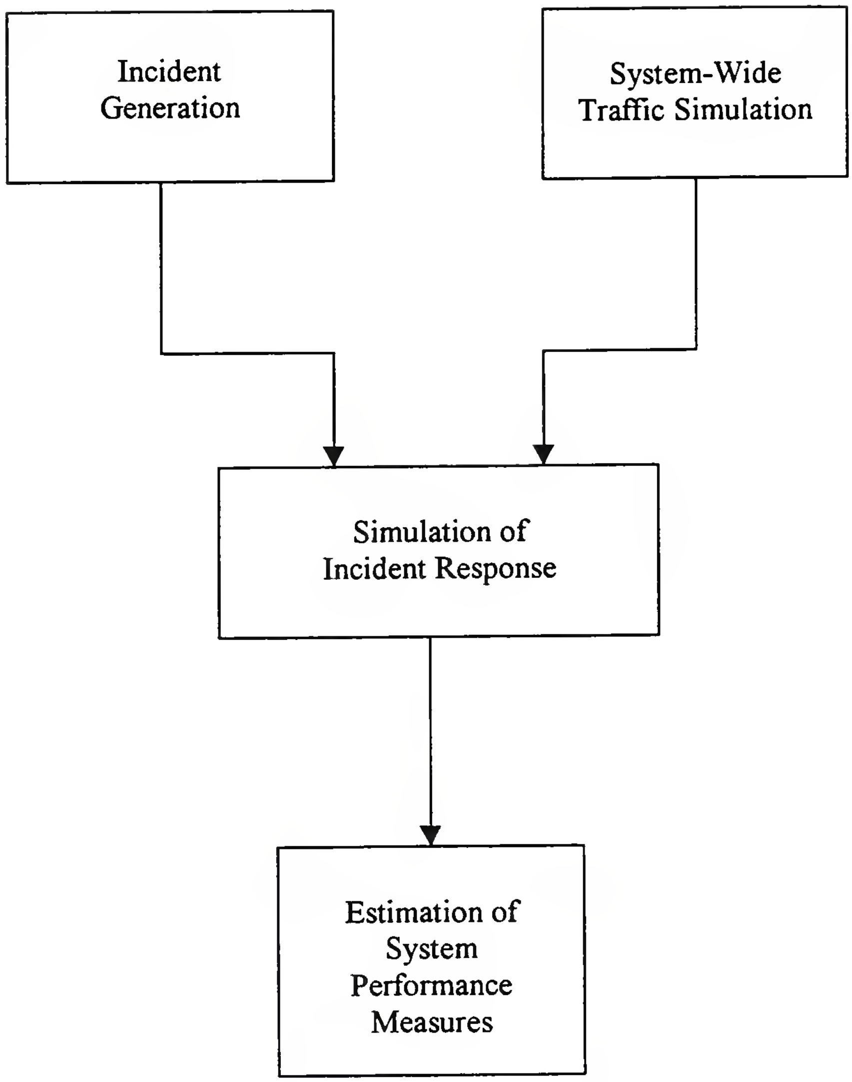


Figure 3.2: Overview of the Simulation Model

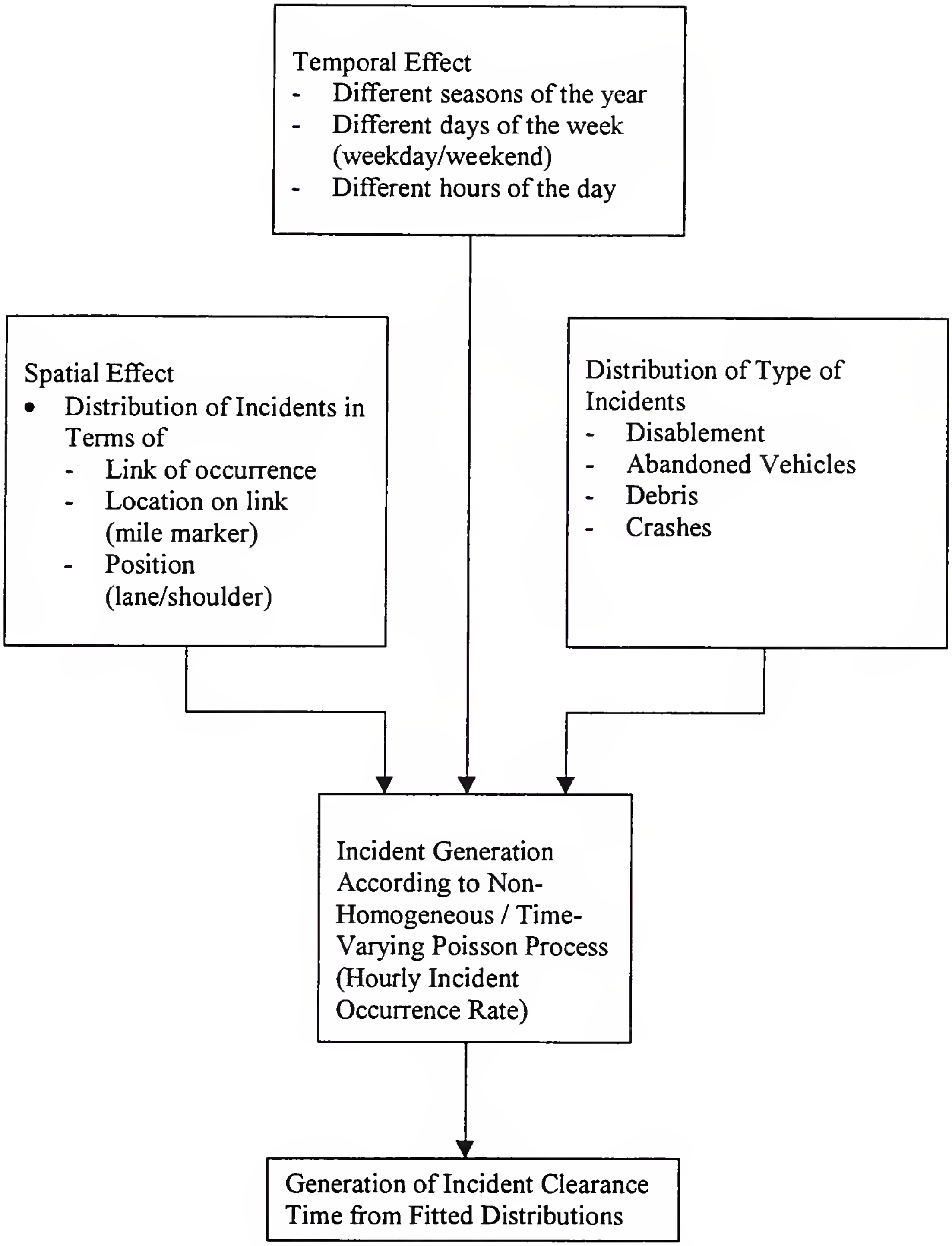


Figure 3.3: Simulation of Incident Generation

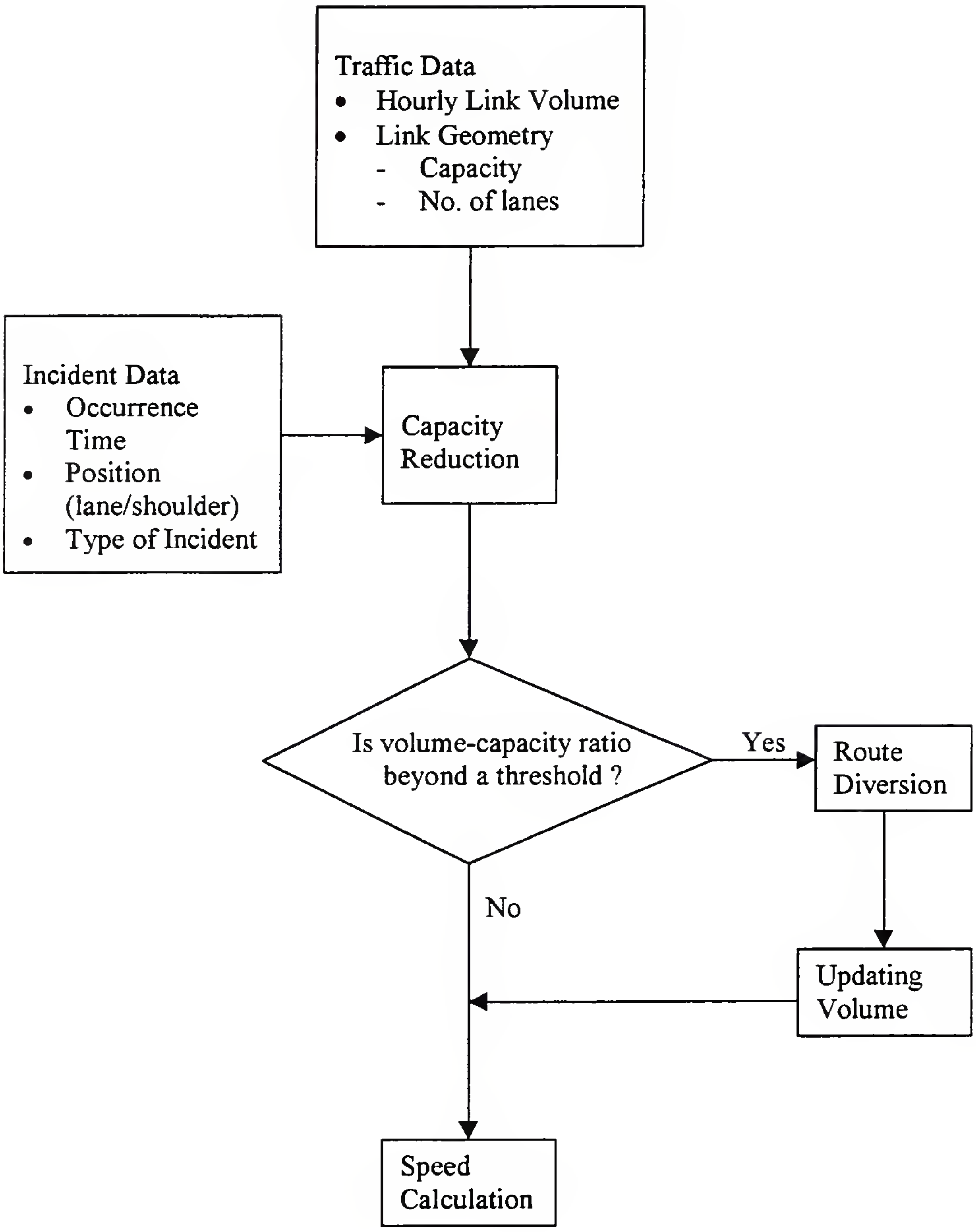


Figure 3.4: Flowchart of Traffic Simulation

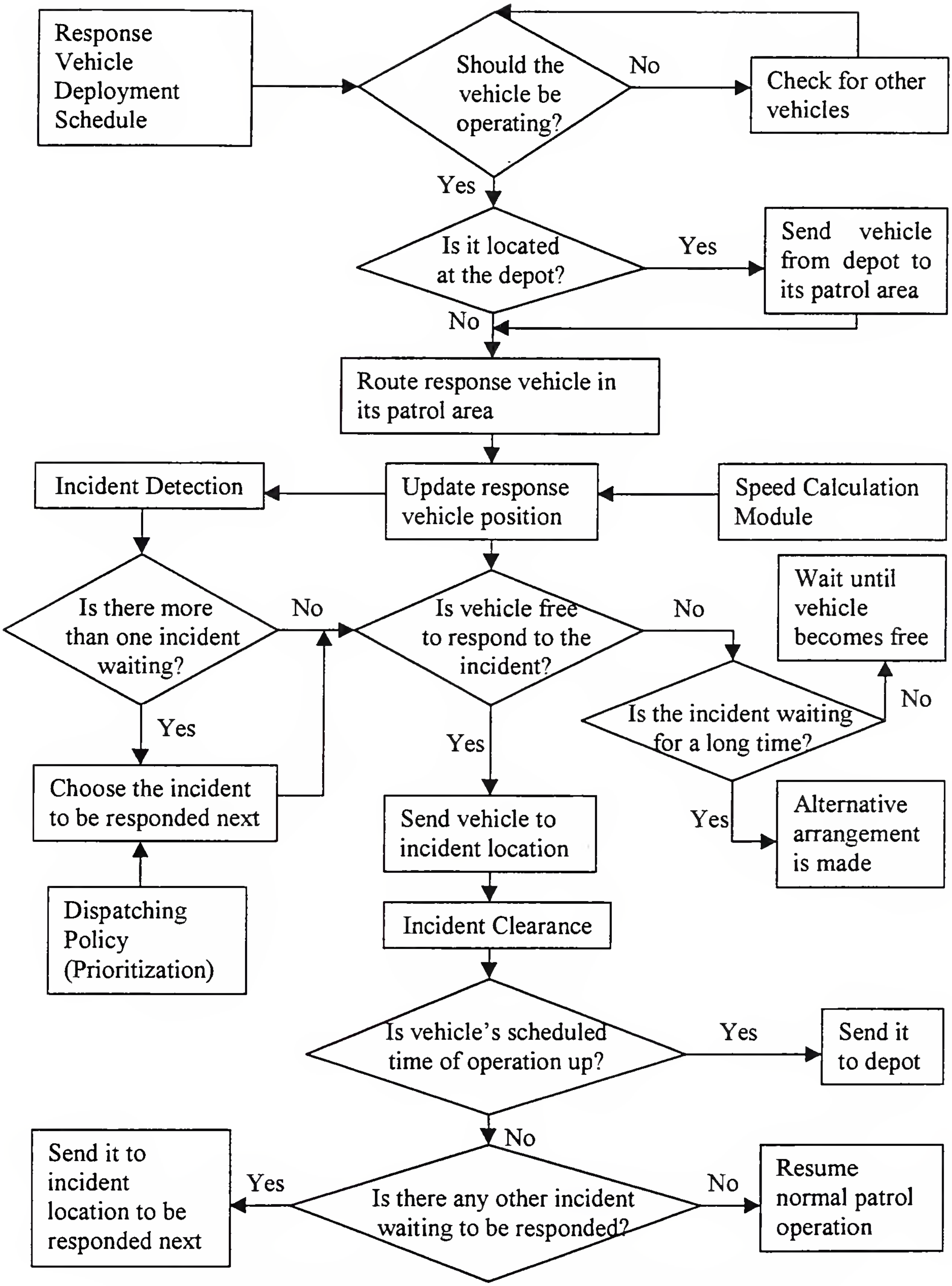


Figure 3.5: Simulation of Operation of Incident Response Vehicles

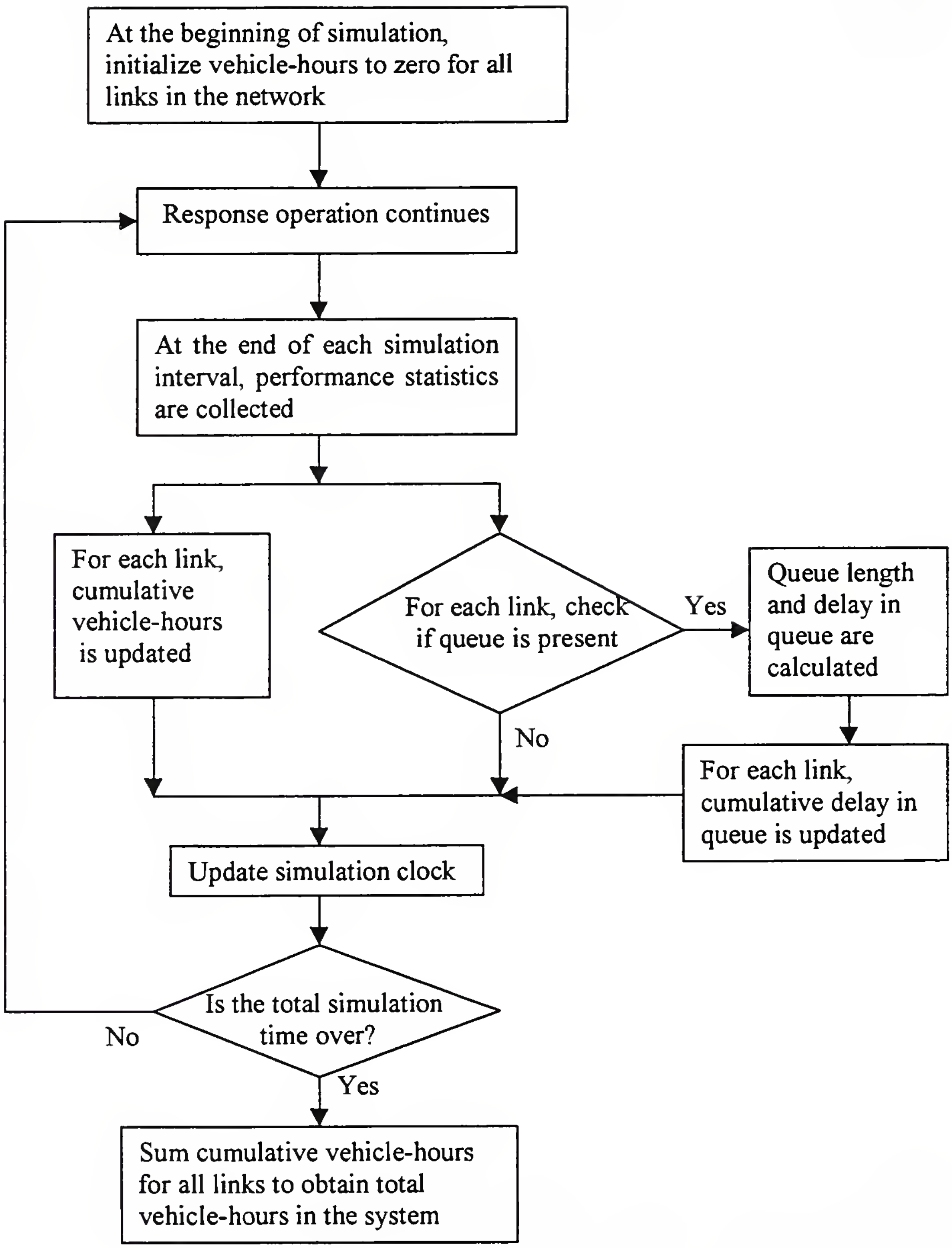
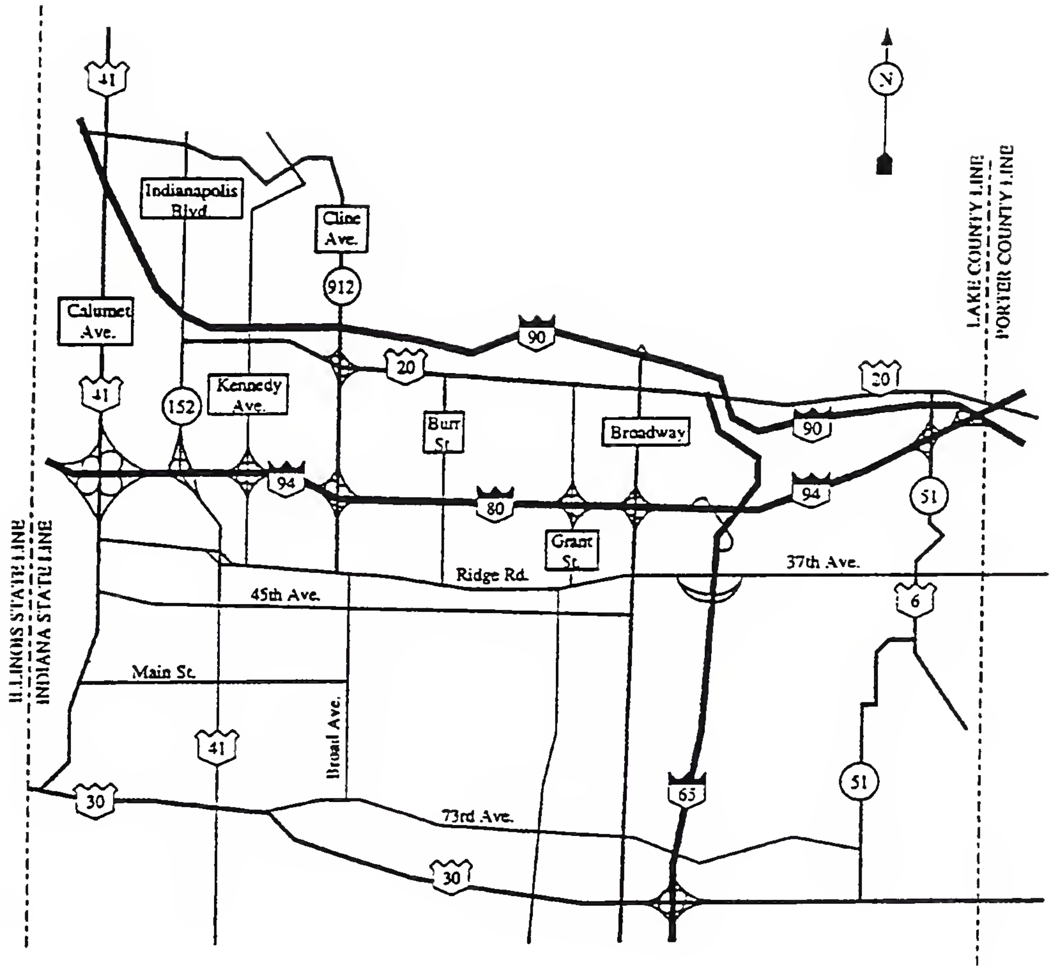


Figure 3.6: Estimation of System Performance Measure



Routes of the Service Patrol :
Along I-80/94 from Illinois State Line to I-90 Interchange and Along I-65 from US-30 to US-20 (close to I-90 interchange)

Figure 3.7: Map of the Hoosier Helper Patrol Area

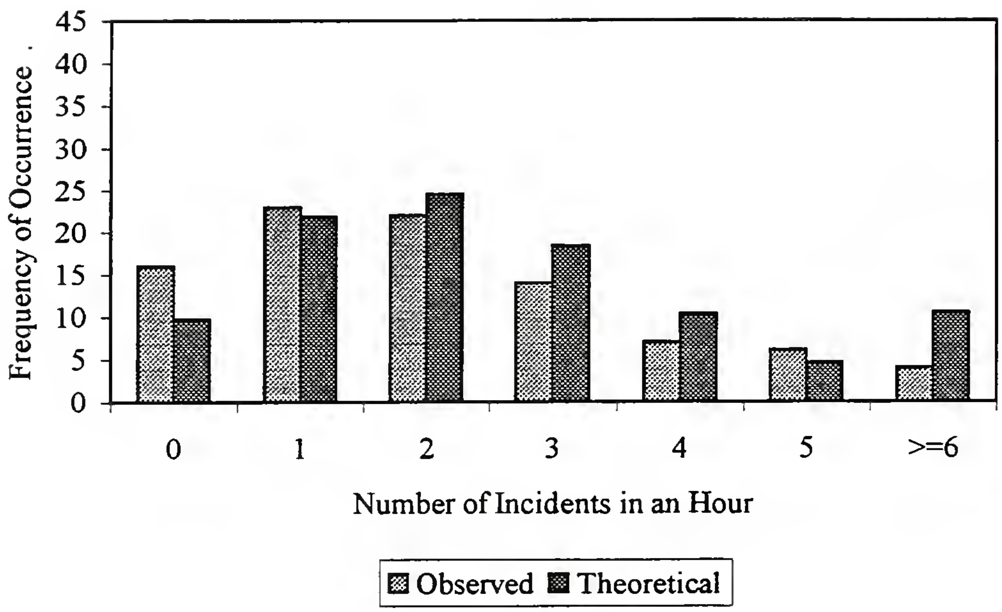


Figure 3.8: Comparison of Observed and Theoretical Frequencies of Incidents occurring in a Particular Hour (8AM-9AM) in the Study Area on Fall Weekdays

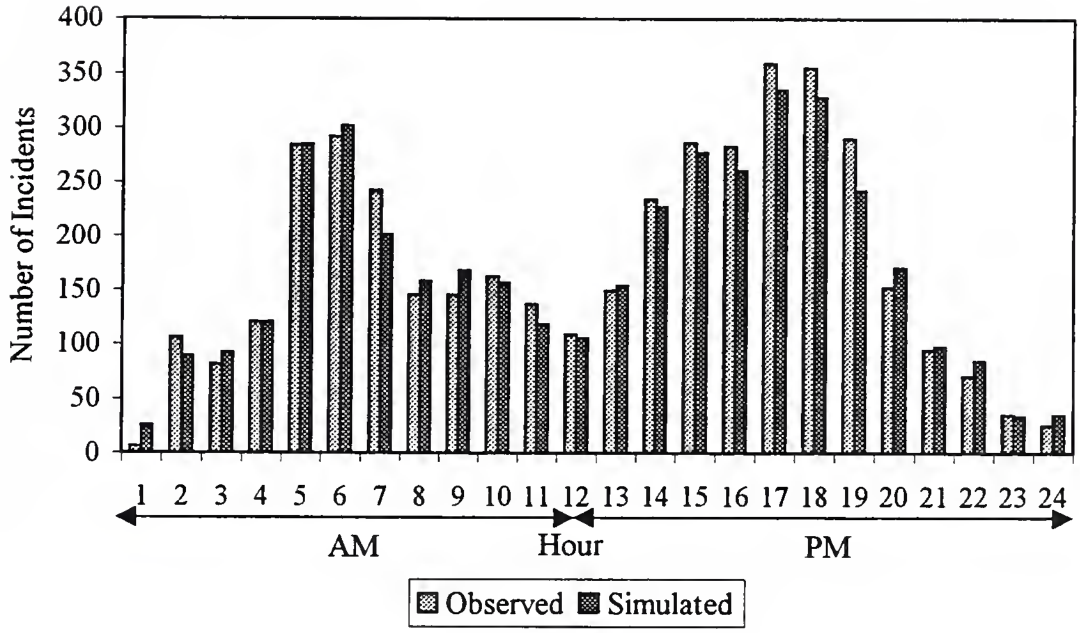


Figure 3.9: Comparison of Simulated and Observed Hourly Incidents in the Study Area on Summer Weekdays

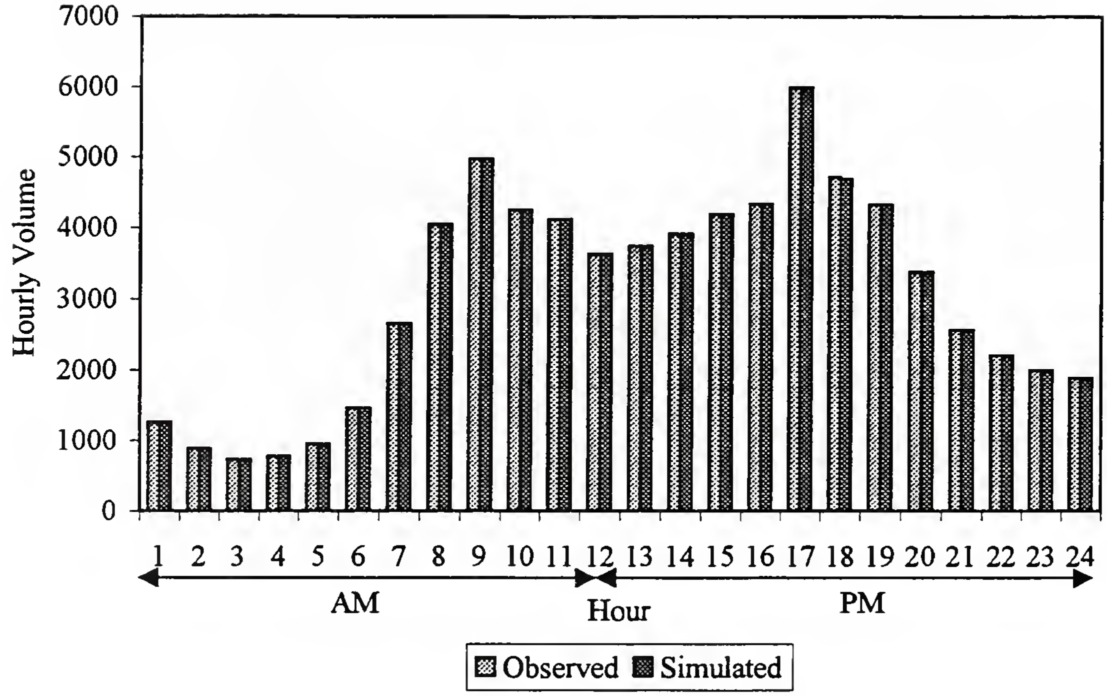


Figure 3.10: Comparison of Simulated and Observed Hourly Volumes on the Westbound Link on the Borman Expressway from Kennedy Avenue to Indianapolis Boulevard

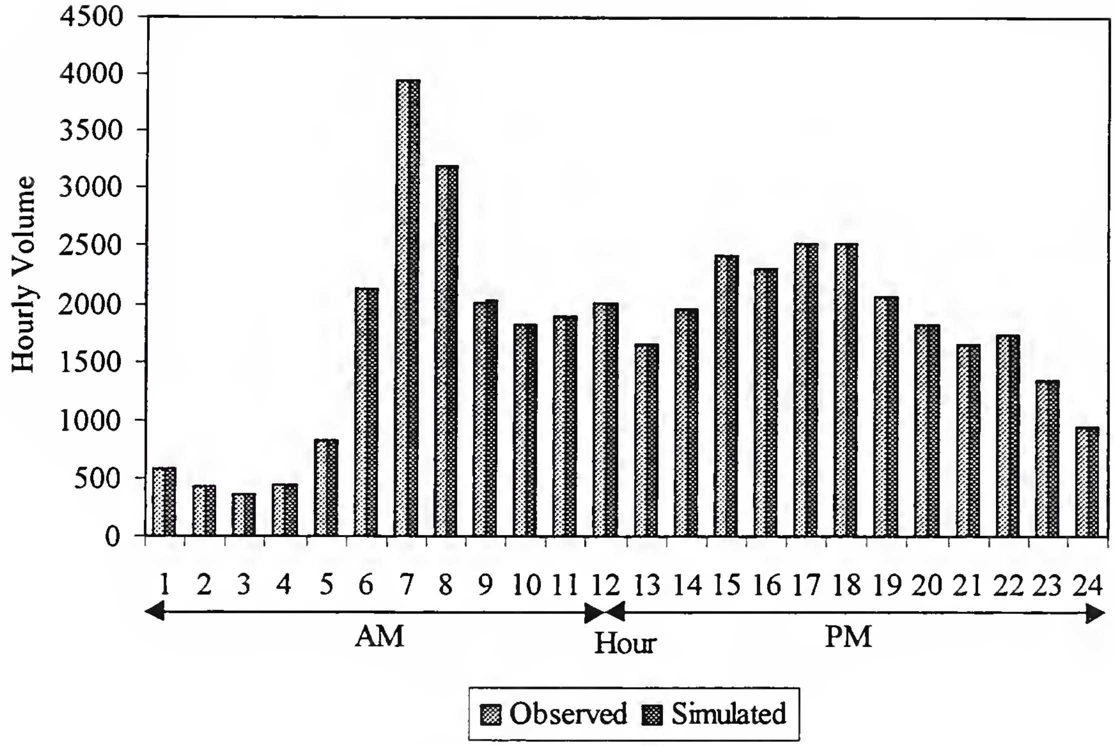


Figure 3.11: Comparison of Simulated and Observed Hourly Volumes on the Northbound Link on I-65 from 37th Avenue to the Borman Expressway Interchange

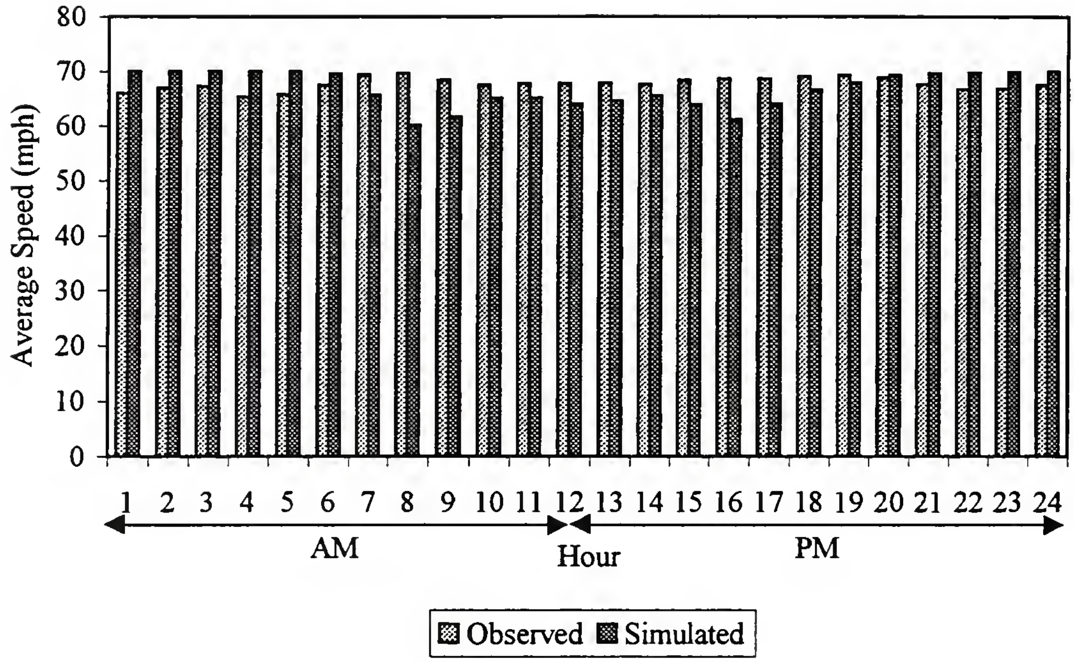


Figure 3.12: Comparison of Simulated and Observed Speeds at Different Hours on the Westbound Link on the Borman Expressway from SR-51 to I-65

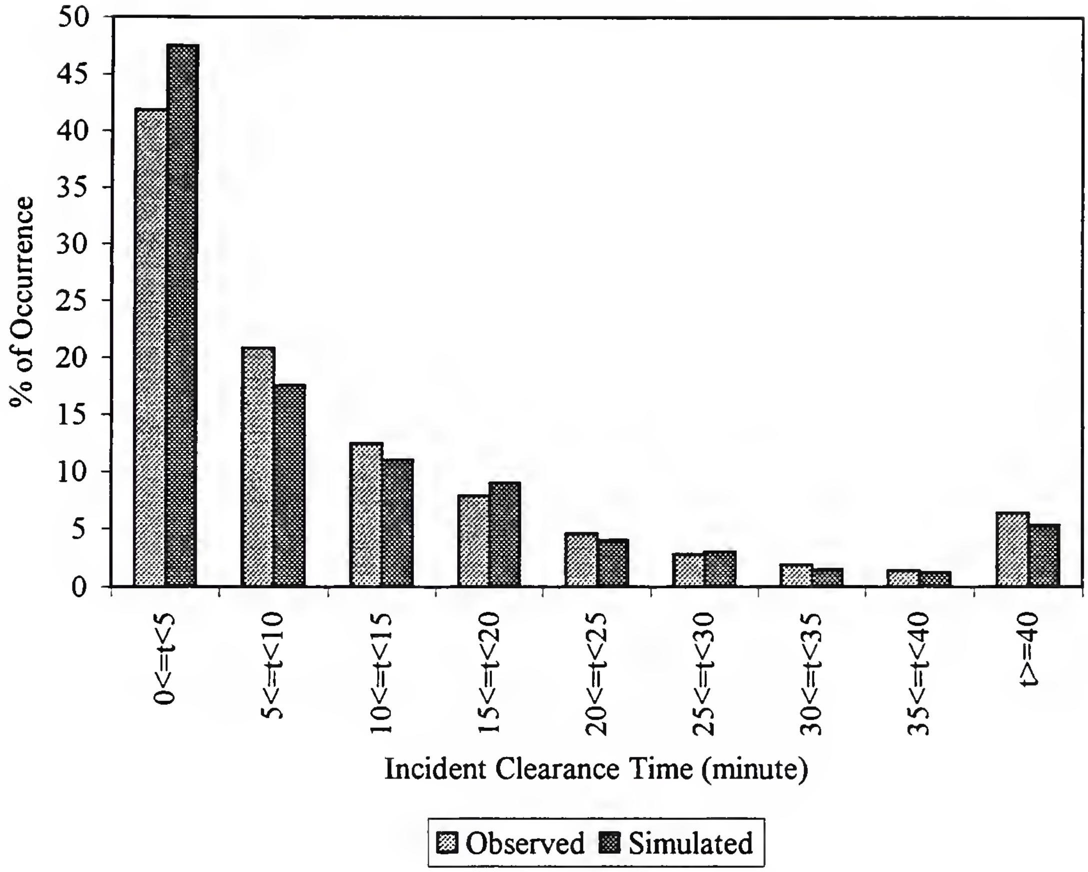


Figure 3.13: Comparison of Simulated and Observed Incident Clearance Times for all Incident Types

CHAPTER 4

METHODOLOGY FOR OPTIMAL SYSTEM DESIGN

4.1 Introduction

The simulation model discussed in Chapter 3 was used to replicate the operation of incident response vehicles through freeway traffic and to incorporate the non-linear impacts of incidents. In order to determine the cost-effective design of an incident response system, a trial-and-error approach could be taken. A sensitivity analysis could be done by changing the parameters of the incident response system, such as fleet size, hours of operation, area of operation, dispatching policies, and routing schemes, in the simulation model and estimating the performance measures. Although such a trial-and-error method may produce a good system design, there is no certainty that the design will be optimal. Moreover, even finding a good design may be very cumbersome, especially when the number and size of decision variables are fairly large, which is the case for most of the existing incident response programs in the United States. Thus, there is a need for devising a systematic methodology that would design the system parameters optimally and efficiently.

4.2 Challenges

Total vehicle-hours, which is the total time spent by all the vehicles in the study network for the given duration of time, was used as the performance measure of the incident response system. One would like to design system parameters such as fleet size, hours of operation, area of operation, dispatching policies, and routing schemes so that the total vehicle-hours is minimized. However, there is no closed-form expression available that can be used to estimate the total vehicle-hours in terms of system parameters. Moreover, the system parameters are not commensurable. Hence, traditional mathematical programming techniques, such as linear programming or integer programming, cannot be directly used. Simulation is the only reasonable way to estimate performance measures with acceptable accuracy and without restrictive assumptions. Therefore, the methodology developed for optimal system design used techniques that involve optimization through simulation.

4.3 Optimization through Simulation

Simulation based optimization is an area that has attracted many researchers. A number of methods have been developed to address such problems. These methods can be divided into six major categories (Carson and Maria, 1997):

a) Gradient Based Search Methods

b) Response Surface Methods

c) Statistical Methods

d) Heuristic Methods

e) A-Teams

f) Stochastic Optimization

Gradient based search methods estimate the response function gradient to assess the shape of the objective function and employ deterministic mathematical programming techniques. Frequently used gradient based search methods are finite differences (Azadivar, 1992), likelihood ratios (Glynn, 1989), perturbation analysis (Ho and Cao, 1991), and frequency domain method (Morrice and Schruben, 1989). In response surface methodology, a series of regression models are fitted to the output variables of a simulation model by evaluating it at several values of the input variables and optimizing the resulting regression function (Daugherty and Turnquist, 1980; Donohue et al., 1990). These methods are primarily intended for continuous decision variables. Unfortunately, the parameters for the incident response system are discrete in nature. Hence, these methods may not be suitable. Statistical methods including ranking and selection (Gupta and Panchapakesan, 1979), and multiple comparison with the best (Hsu and Nelson, 1988) can be used when one may like to choose the best system from a finite number of alternatives. The disadvantage of these methods is that the quality of the solution depends on the set of alternatives chosen. Choosing a good set of alternatives might not be an easy task, especially when the number and size of decision variables are fairly large.

Heuristic methods, such as genetic algorithm (Goldberg, 1989), evolutionary strategies (Schwefel, 1995), simulated annealing (Fleischer, 1995) and tabu search (Glover, 1989 & 1990), are well-established techniques for direct global search. On the other hand, The A-team (asynchronous team) method is a relatively new method that combines various problem-solving strategies so that they can interact synergistically (De

Souza and Talukdar, 1991; Hall and Bowden, 1996). Stochastic optimization methods find the optimal objective function whose values are not known analytically but can be estimated or measured. Some of the notable discrete optimization techniques are the stochastic ruler method (Yan and Mukai, 1992), the stochastic comparison method (Gong et al., 1992), and the method of Andradottir (1995). In each of these stochastic optimization methods, a Markov chain is constructed and almost sure convergence is proved by analyzing the stationary distribution of the Markov chain.

Heuristic methods, as well as discrete stochastic optimization methods, are proven robust techniques. However, they are computationally intensive as many iterations are required to attain the convergence. Parallel computing may be a solution (Fu, 1994). The nested partitions method developed by Shi and Olafsson (1997) is highly compatible with parallel computing. Moreover, the partitioning technique implicitly imposes a structure on the feasible region that can increase the efficiency of the method to a great extent. The nested partitions method divides the solution space into a number of sub-regions and concentrates the search in the sub-regions where good solutions are clustered. As there is no need to search in the entire solution space with the same intensity as in the sub-regions containing the good solutions, the number of iterations to find the optimal solution is reduced considerably (Shi and Olafsson, 1998). Hence, the nested partitions method was used to take advantage of the computational efficiency.

4.4 Nested Partitions Method

In the mathematical notation the problem can be stated as follows. Given a finite feasible region Θ and a performance function $J: \Theta \rightarrow \mathbf{R}$, solve

$$\min J(\theta),\ \forall\ \theta \in \Theta.$$

For any feasible point $\theta \in \Theta$, $J(\theta)$ cannot be evaluated analytically. Often $J(\theta)$ is an expectation of a random estimate of the performance of a stochastic system. Given a parameter θ, it can be expressed as

$$J(\theta) = E[L(\theta)],$$

where $L(\theta)$ is a random variable that depends on the parameter θ. It is assumed that $L(\theta)$ can be estimated using simulation.

4.4.1 Methodology

The basic idea behind the nested partitions method is to sample adaptively from the feasible region (Shi and Olafsson, 1997). The feasible region is partitioned systematically to adapt the sampling and the sampling is concentrated in the subset that is considered the most promising. If the location of a region, where good solutions lie, is known a priori, the search is started from there in the first iteration; otherwise the entire feasible region $\sigma(0) = \Theta$ is taken as the most promising region. Suppose there is a region $\sigma(k) \subseteq \Theta$ that is considered most promising in the k-th iteration. $\sigma(k)$ is partitioned into $M_{\sigma(k)}$ sub-regions, where $M_{\sigma(k)}$ may depend on the subset $\sigma(k)$ but not on the iteration number k. The remaining portion of the feasible region, $\Theta \setminus \sigma(k)$, is aggregated into one region called the surrounding region. At the k-th iteration $(M_{\sigma(k)}+1)$, mutually exclusive subsets are considered that cover the entire feasible region. Samples are taken from each of these sub-regions and are used to estimate the promising index for each region. This index determines which subset becomes the most promising region in the next iteration.

If one of the $M_{\sigma(k)}$ sub-regions is found to be the best, this sub-region becomes the most promising region. If the surrounding region is found to be the best, the method backtracks to the surrounding region and this becomes the new most promising region. The new most promising region is partitioned and sampled in a similar fashion. This generates a sequence of set partitions with each partition nested within the last. The partitioning is continued until eventually all the points in the feasible region correspond to a singleton region that cannot be partitioned further. The subset with the best promising index at this point generates the optimal solution.

4.4.2 Algorithm

The nested partitioning algorithm is described as follows.

Step 1. Partitioning

Partition the most promising region $\sigma(k)$ into $M_{\sigma(k)}$ sub-regions $\sigma_1(k)$, $\sigma_2(k)$, …, $\sigma_{M\sigma(k)}(k)$, and aggregate the surrounding region $\Theta \setminus \sigma(k)$ into one region $\sigma_{M\sigma(k)+1}(k)$. The number $M_{\sigma(k)}$ may depend on the region $\sigma(k)$, but not on the iteration number k.

Step 2. Random Sampling

Randomly sample Nj points θ^{j1}, θ^{j2}, …, θ^{jNj} from each of the subsets $\sigma_j(k)$, and calculate the corresponding sample performance values,

$$L(\theta^{j1}), L(\theta^{j2}), \ldots, L(\theta^{jNj}), j = 1, 2, \ldots, M_{\sigma(k)}+1.$$

The only requirement in the random sampling procedure is that each point in the subset should have a positive probability of being selected. Again the number Nj may depend on the region $\sigma(k)$, but not on the iteration number k.

Step 3. Estimating the Promising Index

The promising index of the sub-region σ_j can be estimated as

$$\hat{I}(\sigma_j) = \min_{i \in \{1,2,\ldots,N_j\}} L(\theta^{ji}),\ j = 1, 2, \ldots, M_{\sigma(k)}+1.$$

It should be noted that very accurate estimate of the promising index is not critical as only the ordinal values affect how the algorithm proceeds. If the sub-region σ_{j^*} contains the true global optimum, then it is sufficient that

$$\hat{I}(\sigma_{j^*}) < \hat{I}(\sigma_j), \forall j \neq j^*.$$

If the above inequality holds, then the correct sub-region is identified.

Step 4. Backtracking

Select the index of the sub-region with the best promising index at the k-th iteration as

$$\hat{j}_k \in \arg \min_{j=1,2.,\ldots,M_{\sigma(k)}+1} \hat{I}(\sigma_j).$$

If more than one region is equally promising, break the tie arbitrarily. If the index corresponds to a sub-region of $\sigma(k)$, then this sub-region would be the most promising region in the next iteration. Otherwise, if the index corresponds to the surrounding region, backtrack to the super-region of the current most promising region. The super-region or the parent region of the current most promising region is the region from which the current most promising region was created by partitioning in the previous iteration and thus has depth one less than the current most promising region. Mathematically the backtracking procedure can be summarized as

$$\sigma(k+1) = \sigma_{j_k}(k), \text{ if } \hat{j}_k < M_{\sigma(k)} + 1$$

$$= s(\sigma(k)), \text{ otherwise,}$$

where $\sigma(k)$ and $\sigma(k+1)$ are the most promising regions in the k-th and (k+1)-th iterations respectively and $s(\sigma(k))$ is super-region of the region $\sigma(k)$.

4.4.3 Example

To illustrate the procedure the example given by Shi and Olafsson (1997) can be presented. Let us consider a feasible region that consists of eight points $\sigma_0 = \Theta = \{1, 2, 3, 4, 5, 6, 7, 8\}$. As can be observed from Figure 4.1, the most promising region is partitioned into two disjoint subsets (i.e. M = 2) in each iteration. At the first iteration, σ_0 is the most promising region and its sub-regions $\sigma_1 = \{1, 2, 3, 4\}$ and $\sigma_2 = \{5, 6, 7, 8\}$ are sampled. If the promising index of σ_1 is better than that of σ_2, then select σ_1 as the most promising region in the second iteration and further partition it to obtain $\sigma_3 = \{1, 2\}$ and $\sigma_4 = \{3, 4\}$. In the second iteration, σ_3, σ_4, and the surrounding region, $(\Theta \setminus \sigma_1) = \sigma_2$, are sampled. If the promising index of σ_3 is the best, select σ_3 to be the most promising region in the third iteration and partition it further into another two sub-regions to obtain $\sigma_7 = \{1\}$ and $\sigma_8 = \{2\}$. On the other hand, if the promising index of the surrounding region, $\Theta \setminus \sigma_1$, is the best, backtrack to σ_0, which is the super-region of σ_1. Now assuming that σ_3 being the most promising region, σ_7, σ_8, and the surrounding region, $\sigma_0 \setminus \sigma_3$, are sampled. If the promising index of σ_7 is the best, select σ_7 as the most promising region. If the promising index of the surrounding region, $\sigma_0 \setminus \sigma_3$, is the best, backtrack to σ_1, which is the super-region of σ_3. The procedure is continued until a most promising region is reached that is singleton (such as σ_7) and hence cannot be partitioned further.

4.4.4 Issues and Features

The nested partitions method is a generalized method; no assumption is needed (Shi and Olafsson, 1997). Moreover, there is the flexibility of implementing both generic and knowledge-based partitioning. The knowledge-based partitioning technique may be implemented if good solutions tend to be clustered together for a given partitioning and some idea can be made about it beforehand. Then this particular sub-region in the solution space can be used as the initial promising region from where the search can be started. If such a partitioning does not exist or a previous idea about it cannot be made, then the generic partitioning is implemented. In that case, the entire solution space is treated as the initial promising region and the search is started from there. The other two important issues are convergence and efficiency. Shi and Olafsson (1998) proved that the nested partitions method converges with probability 1 to a global optimum. They also showed that the method generates high quality solutions reasonably fast.

4.5 Finding Initial Promising Region

As mentioned earlier, the efficiency of the nested partitions method increases to a great extent if a region can be found beforehand where good solutions tend to cluster together. Finding optimal beats is a challenging part of the design of an incident response system, as the number of possible sets of beats is numerous. However, a good beat design can be obtained by balancing the workload among the beats. Workload balancing ensures that all the response vehicles are kept more or less equally busy, which in turn reduces the average response time to an incident (Larson and Odoni, 1981). The idea is to divide the patrol area into a number of beats in such a way that minimizes the difference of workload among all the beats. The workload can be estimated by summing up the incident clearance time of all the incidents occurring on the freeway segments being covered by the patrol program, and a load balancing algorithm can be used to obtain the beat design.

As incidents are random events, the beat design would vary with the incident occurrence pattern. In order to incorporate this randomness in beat design, a concept from sample path optimization (Healy and Schruben, 1991) was used. The idea is to generate incidents randomly for several times with different initial seed points and design beats for each set of incidents, and check if any particular beat design is occurring more frequently than the others. If such a beat design is found, it can be used as the initial promising region. It may so happen that multiple beat designs are found that occur more frequently than the others rather than a single beat design. In such a case, the common features among the most frequently obtained beat designs can be found and a beat design incorporating these common features can be considered as the initial promising region.

4.6 Load Balancing Algorithm

A load balancing algorithm was developed in the present study based on the work by Bodin and Levy (1991). They proposed an algorithm that divides the network into a number of sets of links so that the sum of link costs in each set is close to each other. The algorithm was modified in the present study to enhance the scope of the search for balanced sets of links.

Let us assume that the freeway network has to be divided into N beats. Beats may be referred to as partitions. Each interchange can be treated as a node in the network. Let the freeway segment starting from interchange i to interchange j be denoted as arc (i, j). It should be noted that freeway segments between the same two interchanges with opposite directions of travel should be considered as separate arcs or links. Let t(i, j) be the total incident clearance time for all the incidents on the link (i, j) in a given duration and P be the set of links in partition p. The workload W(p) of partition p can be calculated as follows:

$$W(p) = \sum_{(i,j)\in P} t(i,j).$$

Let Q be a particular partitioning of the network such that the workload of each partition, p, lies between the lower bound t and upper bound T, i.e. $t \leq W(p) \leq T$, p = 1, 2, ..., N. In such a case, the partitioning Q would be called balanced. If the partitioning is not balanced, then at least one partition, p, has a workload which is either less than t or higher than T. Let PEN(Q) be the total penalty of violating the workload bounds over all the partitions in Q and be defined as follows:

$$PEN(Q) = U. \sum_{p=1}^{N} \max(W(p)\text{-}T, 0) + L. \sum_{p=1}^{N} \max(t\text{-}W(p), 0),$$

where U and L are the penalty per unit time for violating the upper and lower bound, respectively. For a balanced partitioning Q, the penalty PEN(Q) = 0. However, many times it may not be possible to obtain such partitioning. In such cases, the objective should be to get a partitioning Q such that PEN(Q) is minimized.

The partitioning should be made in such a way that the following two conditions should hold:

a) Each link in the freeway network should be assigned to one and only one partition (beat).

b) The pair of links between two interchanges representing freeway segments carrying traffic in both directions should be in the same partition (beat).

Also consideration should be given so that all the links in a beat are contiguous and the incident response vehicle can cover all of them in a loop without patrolling any of them more than once. In other words, a beat should preferably be an Euler cycle. The necessary and sufficient conditions for an Euler cycle to exist are that every node be of even degree (Euler, 1953). Fortunately, the nodes (interchanges) in a freeway network are of even degree as freeway segments carrying traffic in two directions are treated as two separate links.

The load balancing algorithm divides the links (arcs) in a freeway network into a set of beats (partitions) of approximately equal workload. It involves four major steps as follows:

a) Initial Seed Point Determination

b) Partitioning

c) Balancing

d) Updated Seed Point Determination

The overall schematic diagram of the load balancing algorithm is presented in Figure 4.2.

4.6.1 Initial Seed Point Determination

Each beat consists of a few nodes and links. At first, a node is selected for each of the beats, and other nodes and links are added to it subsequently to complete the beat design. The node selected first for each beat is called a seed point. Initially, the seed point for the first beat is chosen arbitrarily, i.e. any freeway interchange in the network can be selected as the initial seed point for the first beat. The initial seed point for the next beat is chosen as the node that maximizes its shortest path distance from the first seed point. All the subsequent seed point selections (up to N) are made such that the minimum of their shortest path distances to all previously chosen seed points are maximized.

A fictitious node called supernode is added to the network. A pair of fictitious links for each seed node (called root arcs of the partition) that connect each seed point to the supernode is also added. The workload on these links can be assumed to be zero. The addition of a supernode and root arcs converts the problem to an arc oriented location routing problem with one depot (Levy and Bodin, 1989), as beats would be built out of every root-arc pair. The steps involved in the determination of the initial seed point are summarized in Figure 4.3.

4.6.2 Partitioning

The partitioning step assigns each pair of links in the network to a partition (beat). All partitions are built simultaneously. At any point in this step, the partition with the least amount of workload assigned to it so far becomes the next candidate partition for expansion. The pair of links added to this partition is the pair with the highest workload that is adjacent to one of the nodes already in the partition. Thus, each partition is guaranteed to remain connected and the difference between the partitions with the highest and lowest workload is kept as small as possible. The schematic diagram for partitioning is presented in Figure 4.4.

4.6.3 Balancing

The partitions created by the partitioning step may not be balanced. The balancing step tries to move the link pairs between partitions in order to bring the workload all the partitions between t and T while maintaining the connectivity. Different types of swaps are used to interchange pairs of links between partitions. It can be a multiple arc pair swap or a single arc pair swap. Multiple arc pair swaps include multiple leaf swaps as well as branch swaps, while single arc pair swaps include single leaf swaps as well as cycle swaps. Examples of multiple leaf swap, branch swap, single leaf swap, and cycle swap are presented in Figures 4.5, 4.6, 4.7, and 4.8 respectively. Implementation of a particular type of swap depends on the configuration of the partitions in the network. A detailed description of these swaps is presented in Levy and Bodin (1989).

While multiple arc pair swaps attempt to make large improvements by moving several pairs of links from one partition to another, single arc pair swaps make smaller improvements by moving only a single pair of links. Both types of swaps are used sequentially as shown in Figure 4.9. The partition with the highest penalty is chosen first for swapping. All the potential swaps of a particular type (multiple arc pair swap or single arc pair swap) that further reduce the penalty are investigated and finally the one that reduces the penalty by the highest amount is implemented. The procedure is repeated until all the potential improving swaps are exhausted. The common steps involved in both types of swaps are described in the schematic diagram presented in Figure 4.10. The use of a multiple leaf swap and a branch swap in a multiple arc pair swap and the use of a single leaf swap and a cycle swap in a single arc pair swap are presented in Figures 4.11 and 4.12, respectively.

4.6.4 Updated Seed Point Determination

If the partitions after the balancing step are not satisfactorily balanced, a new set of seed points are generated. The new seed point for a partition is chosen such that the maximum of its shortest path distances to all other nodes in the same partition is minimized. However, there are two restrictions in choosing the new seed point. They are as follows:

a) No two partitions can have the same node as the seed point.

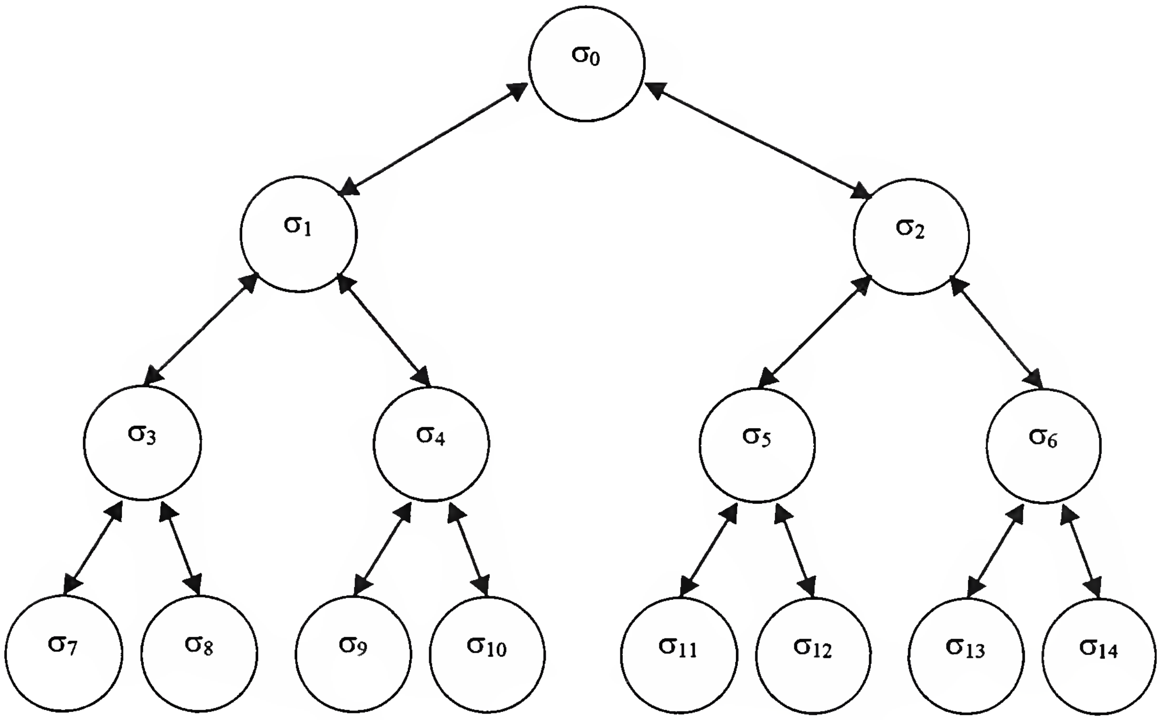
b) A new seed point of one partition may not be the seed point of another partition in the previous iteration.

The steps involved in the determination of an updated seed point are shown in Figure 4.13. After the new seed points are obtained, the partitioning and balancing steps are followed. The entire process is repeated, as shown in Figure 4.2, until all possible seed points are exhausted. Finally, the best set of partitions obtained is chosen as the good beat design that would be subsequently used as the initial promising region in the nested partitions method described in Section 4.4.

4.7 Overall Framework for Designing Incident Response System

The simulation model, developed to replicate the operation of incident response vehicles, is described in Chapter 3. The nested partitions method for optimization through simulation and a load balancing algorithm for finding the initial promising region are discussed in Sections 4.4 and 4.6, respectively. In this section, an attempt is made to synthesize all these methodological components.

The schematic diagram of the overall framework is presented in Figure 4.14. The incident data collected in the study area were used as input to the incident generation module that was used to generate incidents randomly for a given duration. The workload for each of the links in the freeway network can be estimated by summing up the time needed to clear the incidents occurring on it during that period. The area of operation was divided into a number of beats using a load balancing algorithm such that the difference in workload among the beats would be minimized. The beat design so obtained can be used in the nested partitions method as the initial promising region from where the search for the optimal solution starts. The nested partitions method adaptively samples from the feasible region and focuses the search in the region where all the good solutions tend to cluster. A simulation model was used to evaluate the performance of various good designs chosen by the nested partitions method. The performance measures of these designs, estimated by the simulation model, were used to obtain new promising regions that were consequently used in the nested partitions method to refine the search. The process was repeated until the optimal solution was obtained.



σ_0 = Most Promising Region at the First Iteration
(Obtained from Load Balancing)

Figure 4.1: Partitioning Generated by the Nested Partitions Method
(Source: Shi and Olafsson, 1997)

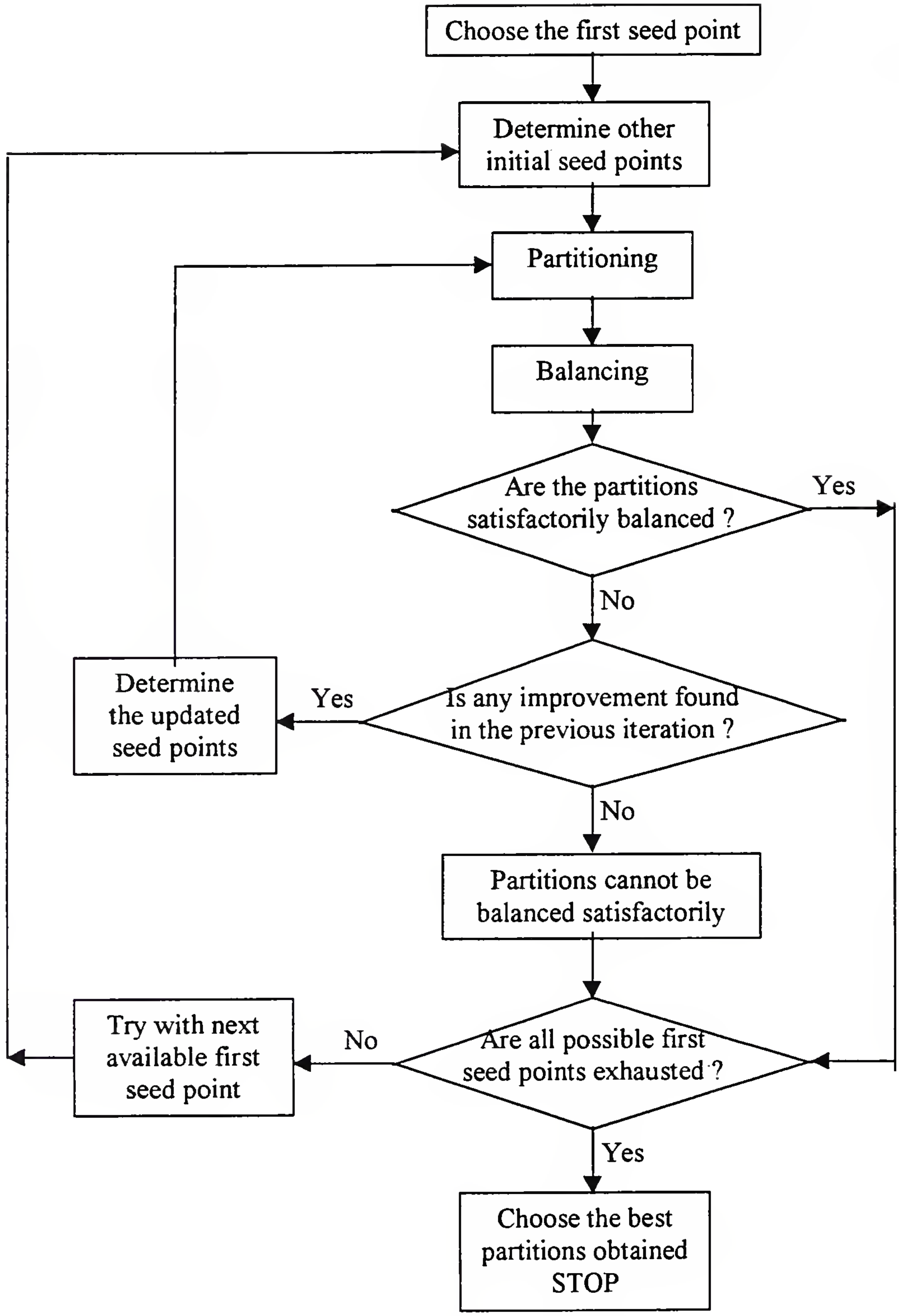


Figure 4.2: Schematic Diagram for Load Balancing Algorithm

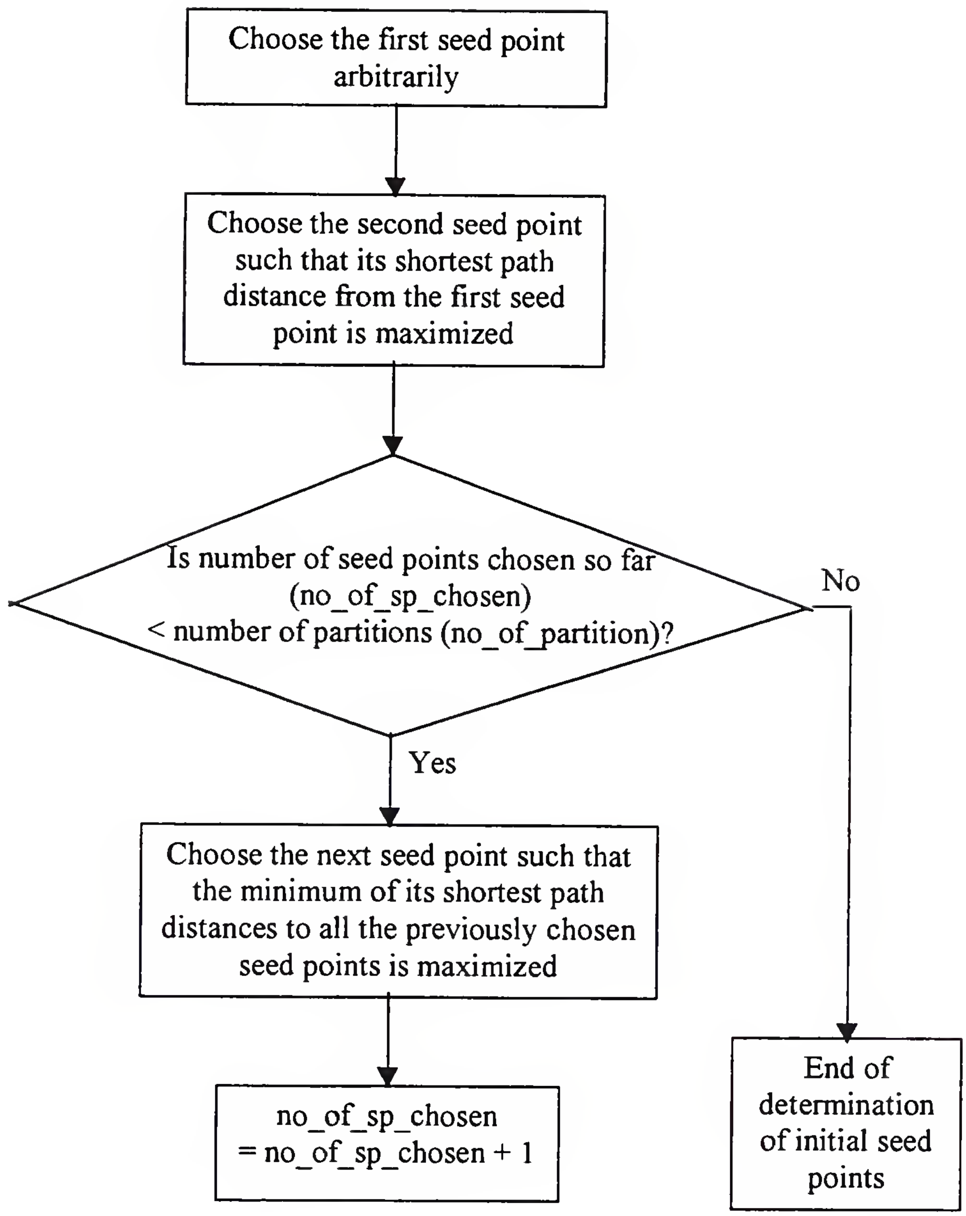


Figure 4.3: Steps Involved in Determination of Initial Seed Points

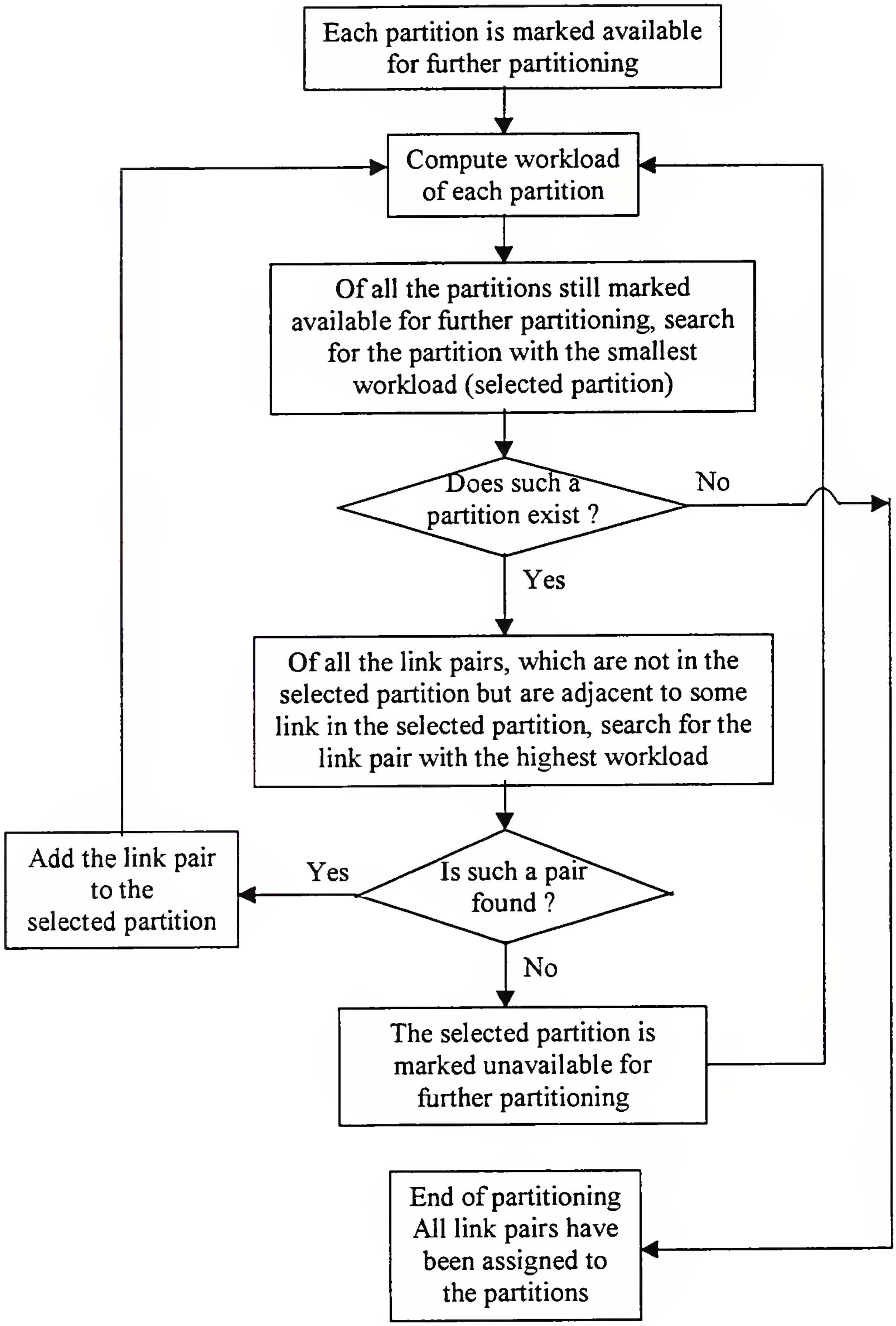
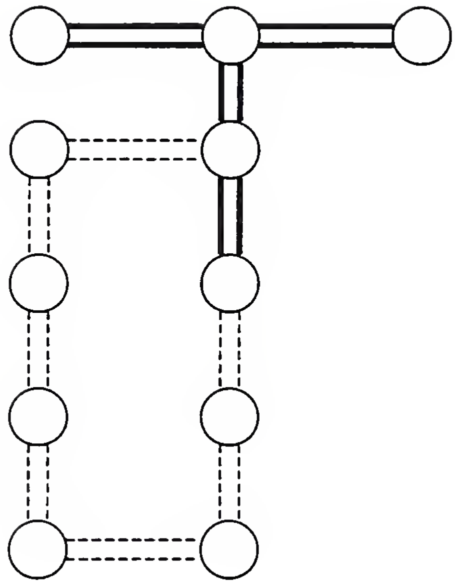


Figure 4.4: Steps Involved in Partitioning

Before Swap



After Swap

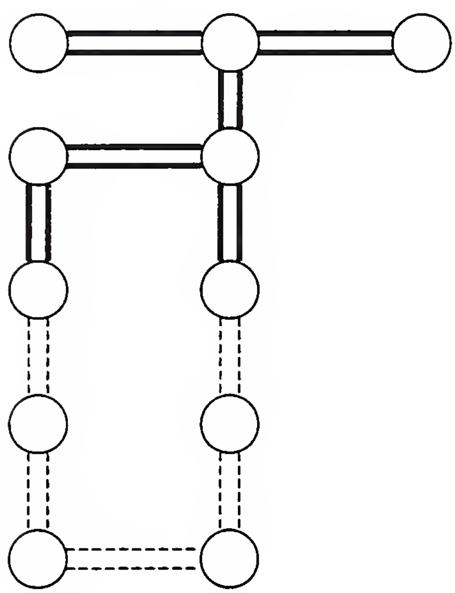
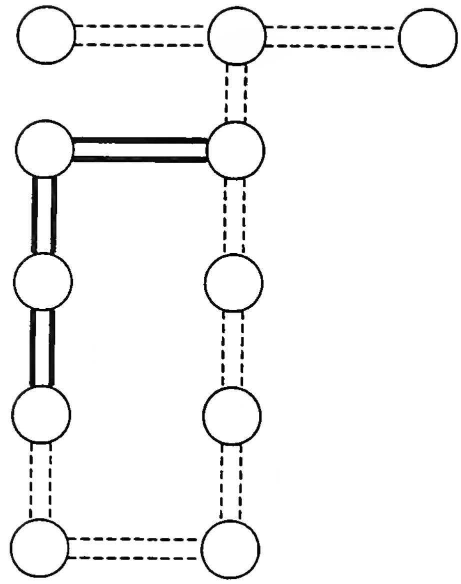


Figure 4.5: Example of a Multiple Leaf Swap Used in Balancing

Before Swap



After Swap

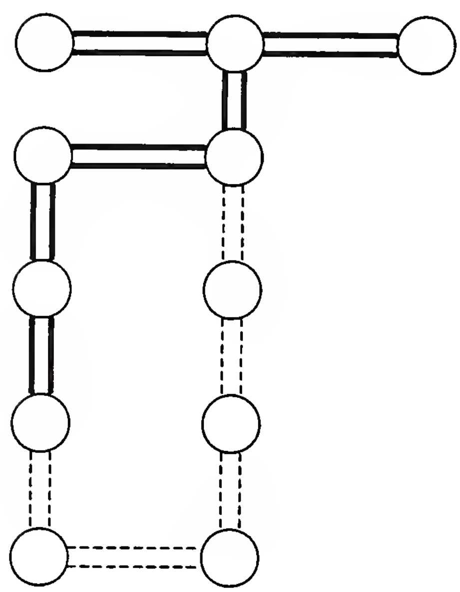
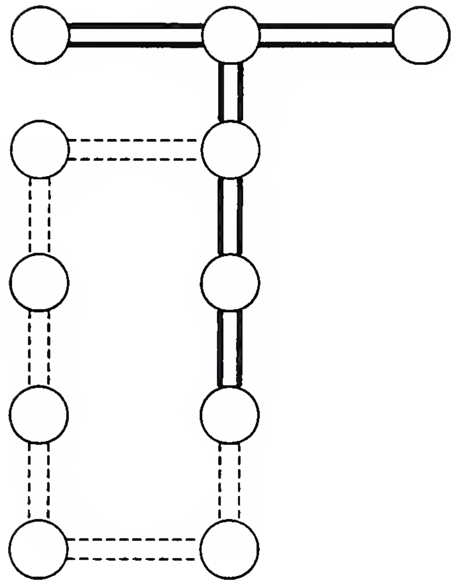


Figure 4.6: Example of a Branch Swap Used in Balancing

Before Swap



After Swap

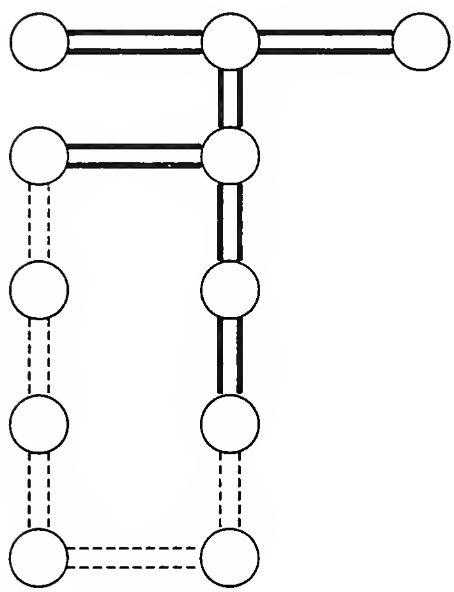
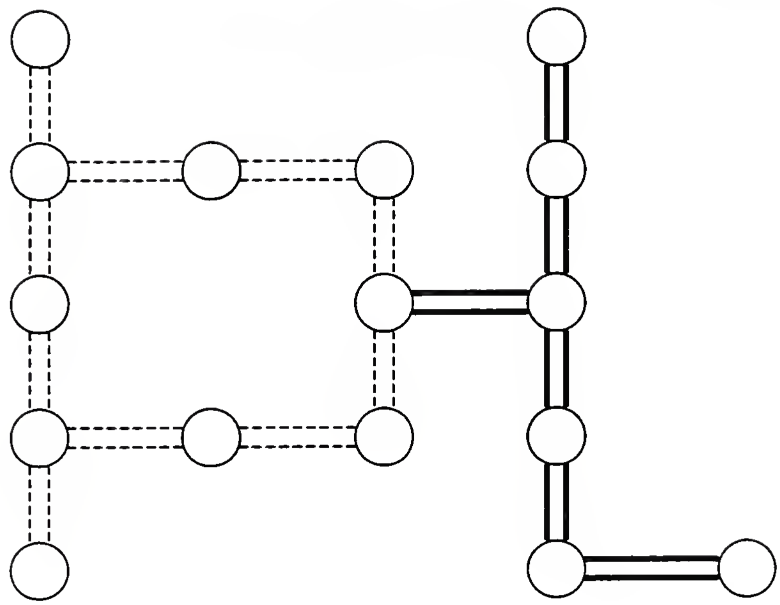


Figure 4.7: Example of a Single Leaf Swap Used in Balancing

Before Swap



After Swap

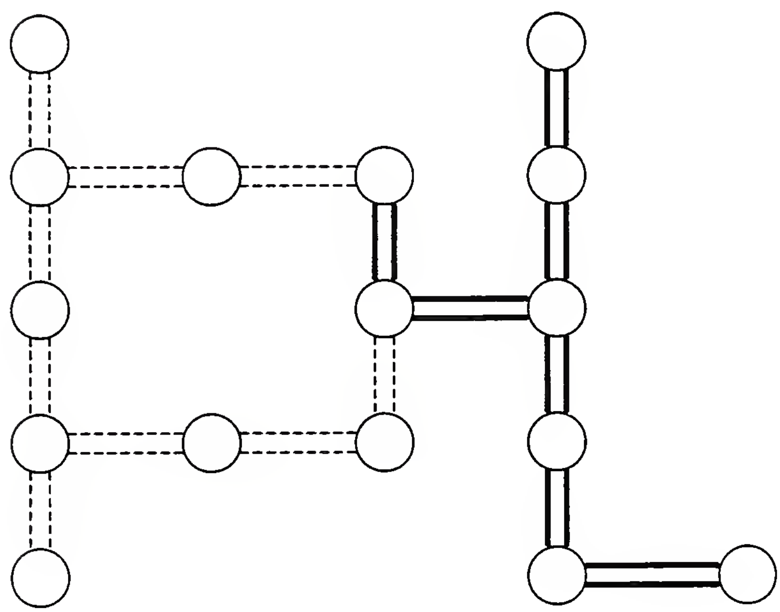


Figure 4.8: Example of a Cycle Swap Used in Balancing

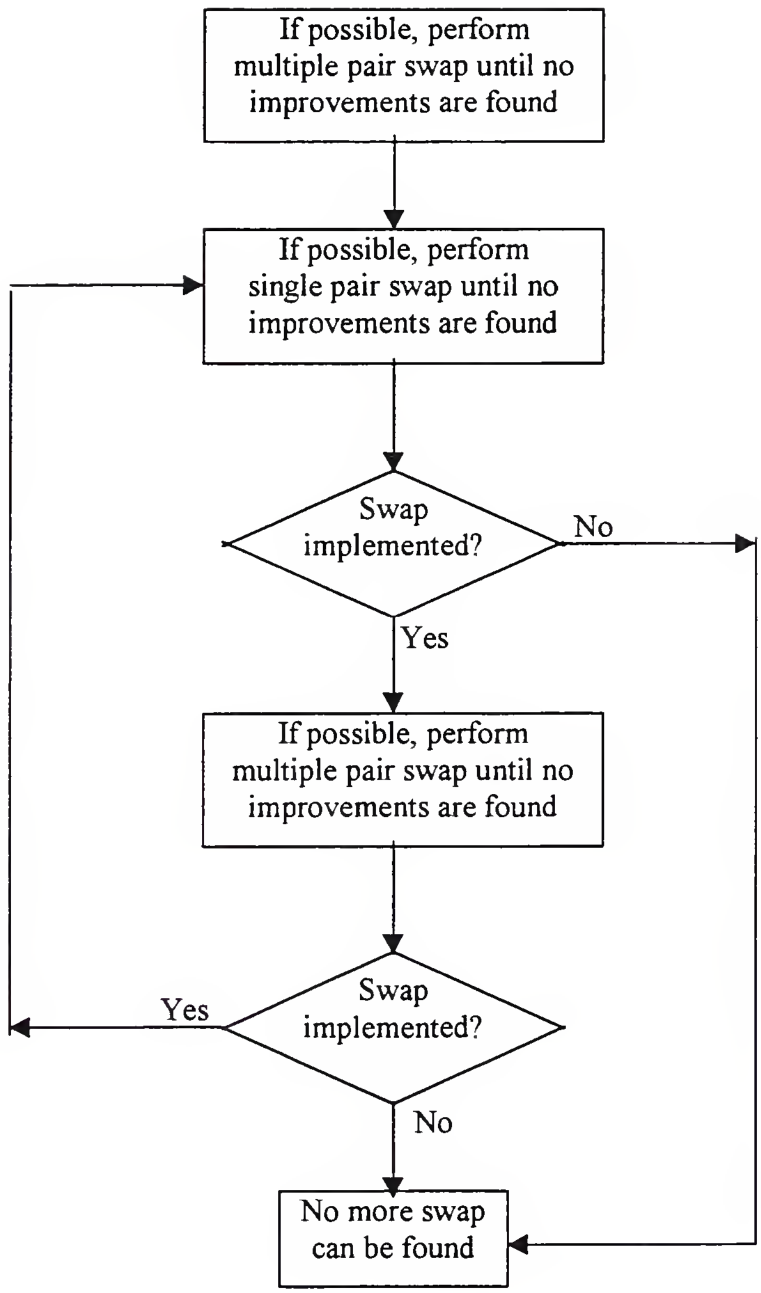


Figure 4.9: Steps Involved in Balancing

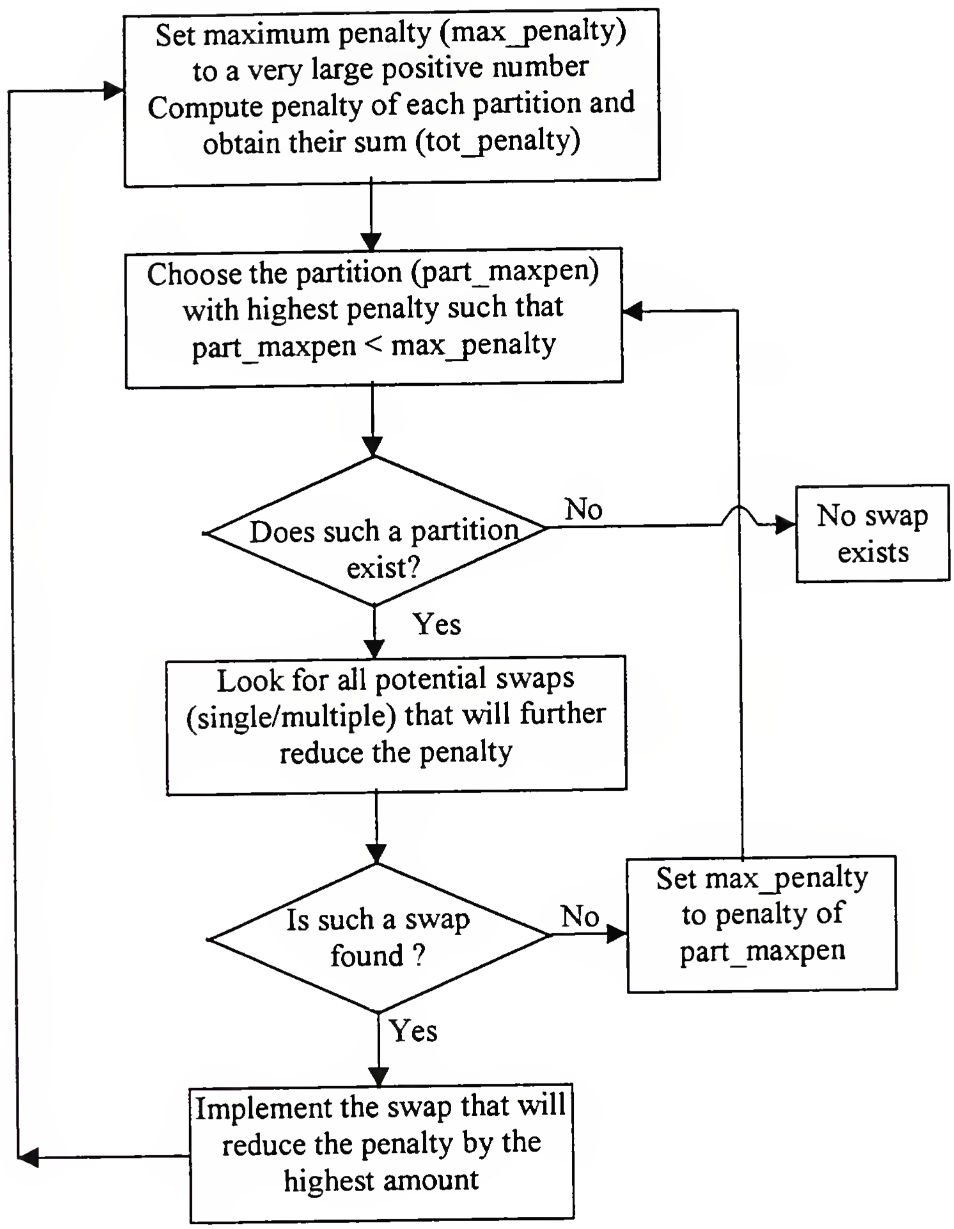


Figure 4.10: Common Steps in Single and Multiple Pair Swaps

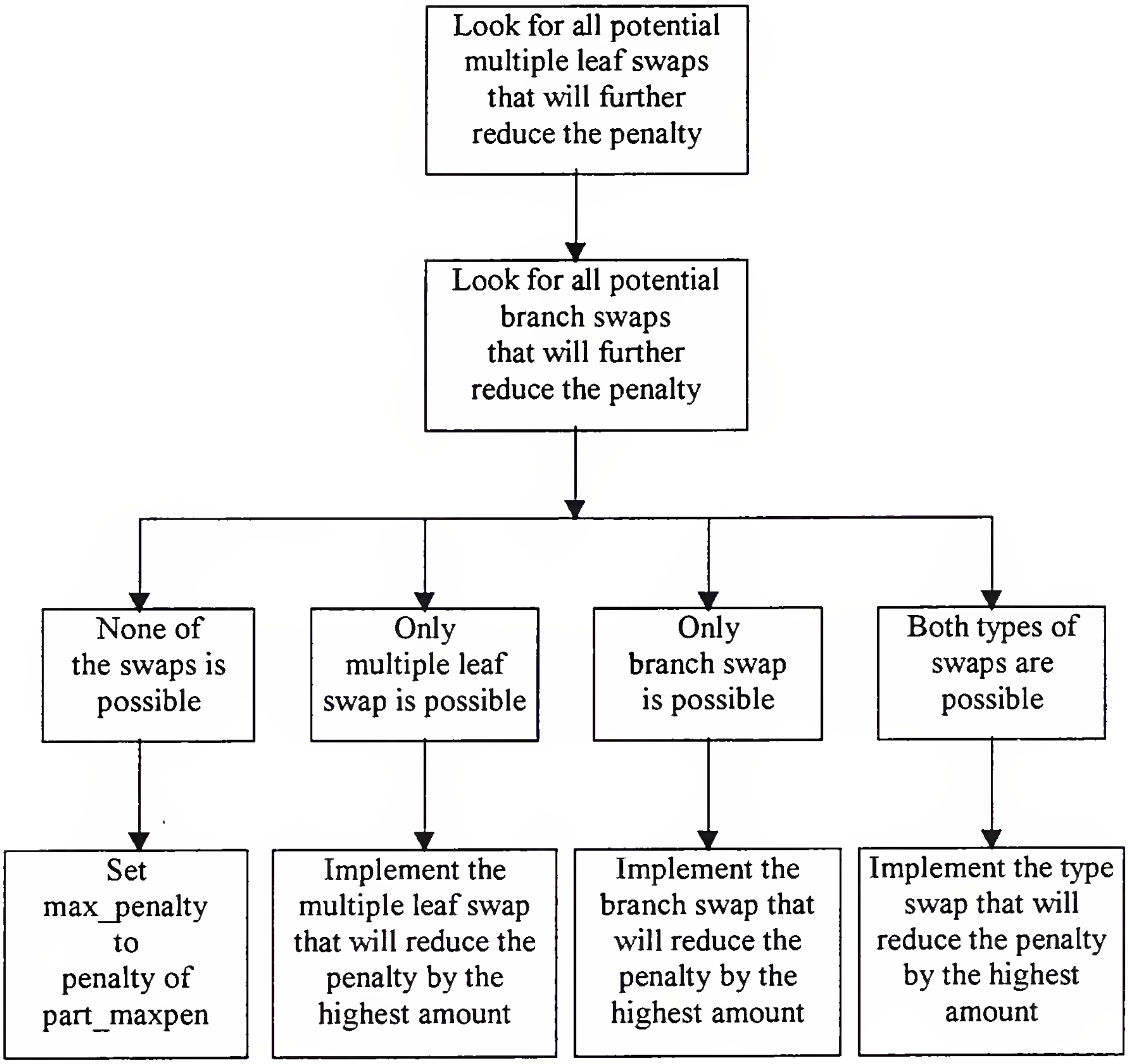


Figure 4.11: Use of Multiple Leaf Swap and Branch Swap in Multiple Pair Swaps

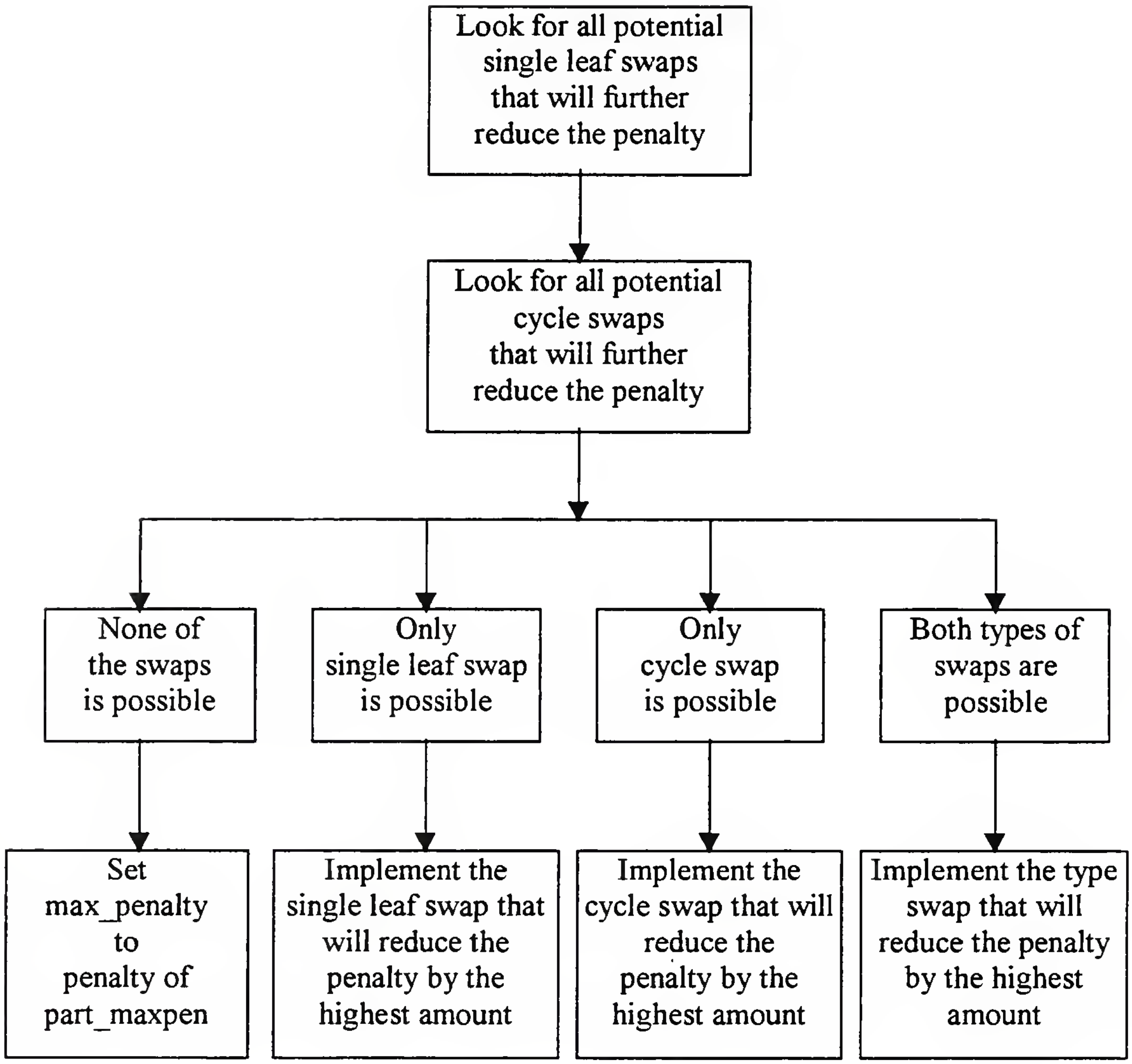


Figure 4.12: Use of Single Leaf Swap and Cycle Swap in Single Pair Swaps

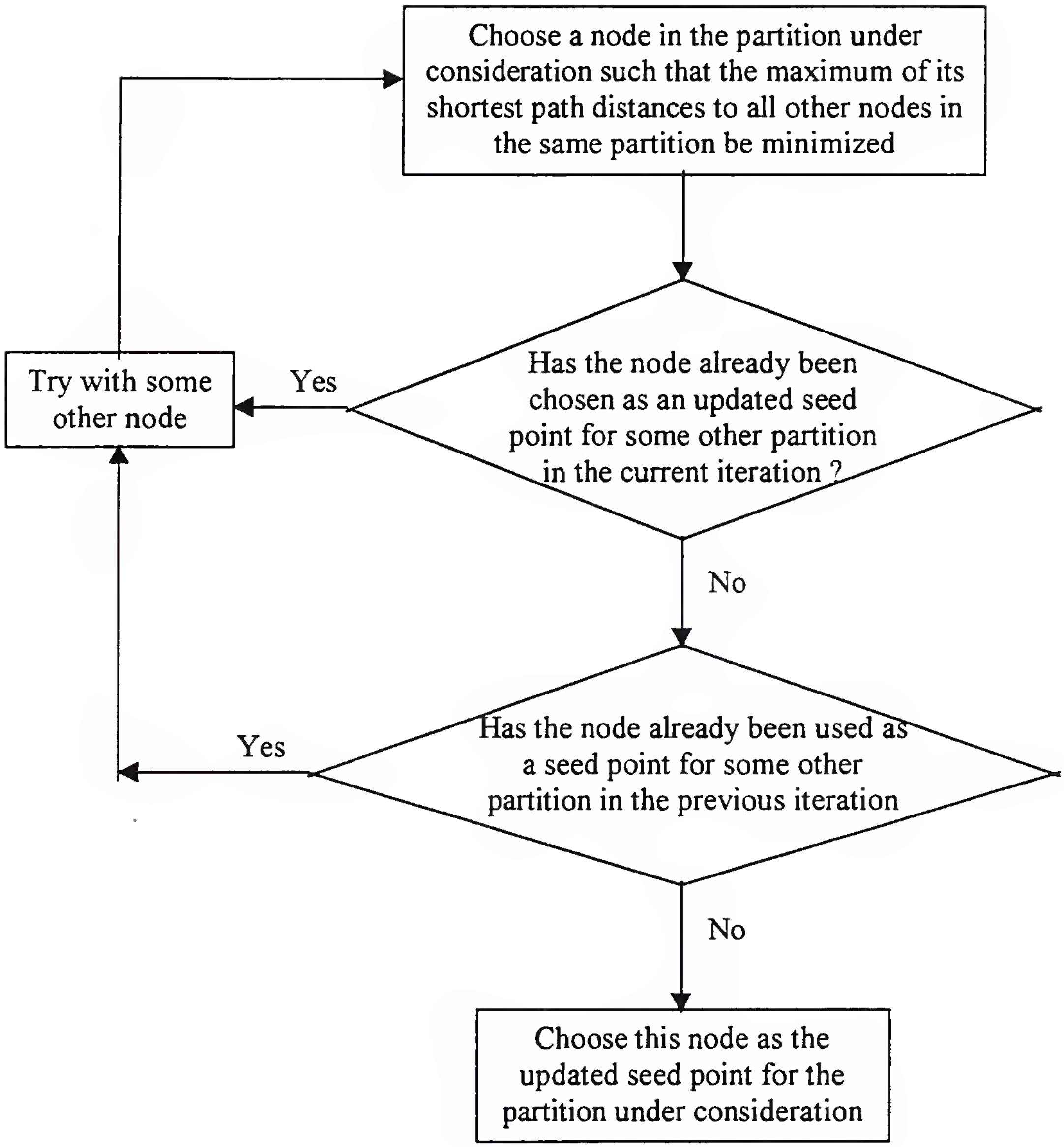


Figure 4.13: Steps Involved in Determination of Updated Seed Points

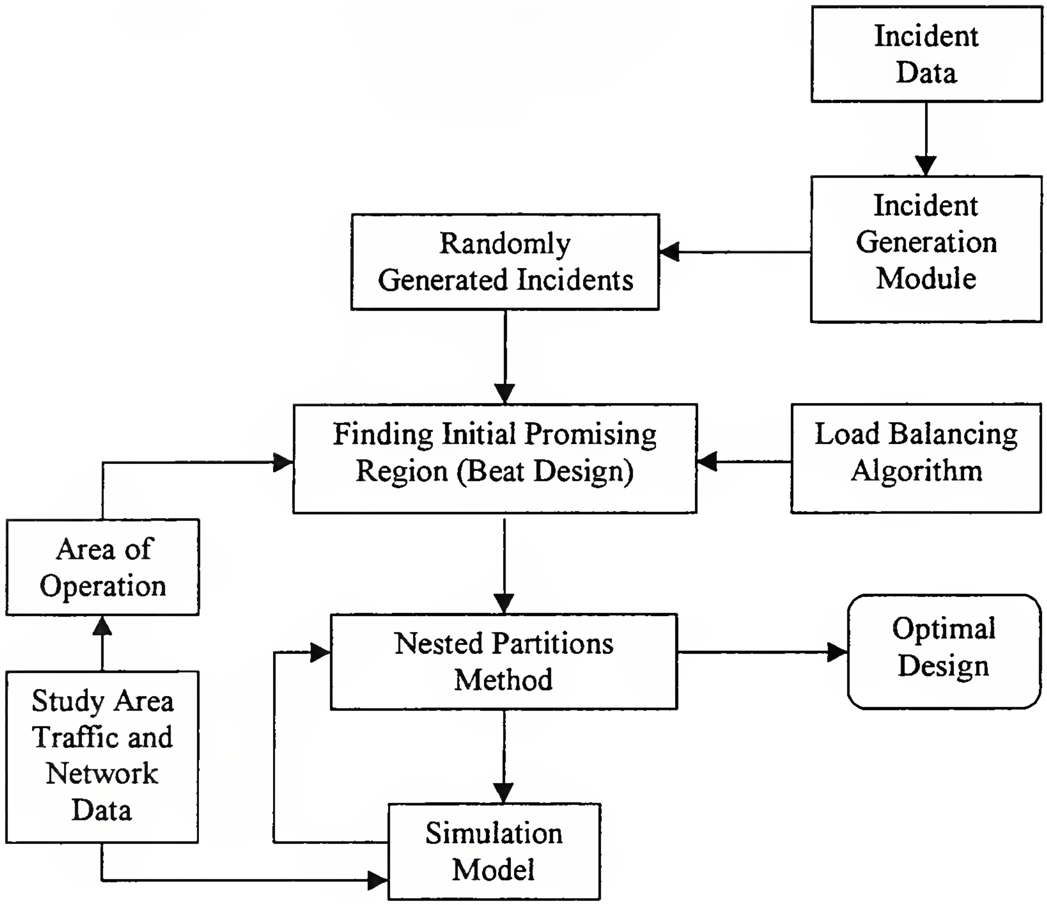


Figure 4.14: Overall Framework for Designing Incident Response System

CHAPTER 5

STUDY RESULTS

5.1 Example Problem

The methodology for the optimal design of an incident response system has been discussed so far. As an example application of the proposed methodology, the case of the Hoosier Helper patrol program in northwest Indiana is presented. The Hoosier Helper program is a roving freeway service patrol program supported by the Indiana Department of Transportation (INDOT). Hoosier Helper crews regularly patrol a sixteen mile stretch of the six-lane Interstate 80-94 freeway near Gary, commonly known as the Borman Expressway, seeking and responding to incidents. At least two response vehicles are in service 24 hours a day, seven days a week. In addition, during peak travel periods, another extra vehicle is deployed to cover a portion of the four-lane Interstate 65 freeway (I-65). A detailed description of the Hoosier Helper program is presented in Chapter 3. In this chapter it is shown how the proposed methodology can be used to improve the efficiency of the program utilizing existing resources. The example also indicates how efficiency can be further enhanced by effectively allocating additional resources such as increased fleet size and deployment of automatic incident detection system.

5.2 Results for the Example Problem

The network of the Borman corridor used in the example problem is presented in Figure 5.1. The figure indicates the portion of the Borman Expressway and I-65 patrolled by the Hoosier Helper program. The network includes parallel arterial roads that can be used by traffic diverted from the freeway. The portion of a freeway/road segment between two interchanges/intersections is termed as a link and an interchange/intersection is termed as a node. There are 38 nodes and 120 links in the study network. The freeway/road segment for each direction of travel is treated as a separate link. Currently, three response vehicles are deployed in the peak period (from 6:00 AM to 10:00 AM and from 3:00 PM to 7:00 PM). During the off-peak period (from 10:00 AM to 3:00 PM and from 7:00 PM to 10:00 PM) two response vehicles patrol the Borman Expressway. I-65 is not covered during this period. Also during the night time operation (from 10:00 PM to 6:00 AM) two response vehicles are deployed and I-65 is not covered. The rate of incident occurrence, as well as traffic volume during the peak period, are much higher than the corresponding values in the off-peak period and at night. Thus, the adverse effect of incidents is most severe in the peak period.

5.2.1 Routing Schemes

While patrolling the freeway, all response vehicles do not cover all segments. The freeway segments to be patrolled by the incident response program are divided into a number of beats and each vehicle is given the primary responsibility of finding and responding to incidents in its respective beat. It is important to design these beats intelligently as the incident detection time, as well as response time, depend heavily on beat configuration. In this section, it is shown how the optimal beat configuration can be obtained using the proposed methodology.

5.2.1.1 Description of the Procedure Adopted for Beat Design

At first, the case of optimal beat design with three response vehicles patrolling during the peak period is considered. A load balancing algorithm was used to come up with the initial beat design that was subsequently used in the nested partitions method as a starting point. Using the load balancing algorithm the patrol area was divided into three beats in such a way that the difference of workload among the three beats was minimized. The workload was calculated by summing up the incident clearance time of all the incidents occurring on the freeway segments being covered by the patrol program. Incidents were generated randomly for a period of 20 days using the simulation model described in Chapter 3.

As incidents are random events, the beat design would vary with the incident occurrence pattern. In order to incorporate the stochastic component in the beat design, a concept from sample path optimization was used. The idea is to generate incidents randomly with different initial seed points and design beats for each set of incidents, and check if any particular beat design is occurring more frequently than the others. The most frequently occurring beat design can be used as a starting point in the nested partitions method. It may so happen that multiple beat designs are found instead of a single design that occur more frequently than the others. In such cases, common features among the most frequently obtained beat designs may be found and a beat design incorporating these common features can be used as a starting point.

5.2.1.2 Application of the Procedure Adopted for Beat Design

Thirty simulation runs were made, each for 20-day period, with different random number seeds from independent streams to generate incidents, and subsequently, the load balancing algorithm was used to divide the patrol area into three beats. Although beat design was made independently 30 times, only 6 types of design, as shown in Figures 5.2 through 5.7, were obtained. It can be observed from Figure 5.8 that design 3 was obtained the most number of times. There is a common feature among designs 1 through 4. The first beat remained the same as it consisted of links 1 through 10 for each of these four designs. This was used as an initial promising region for the nested partitions method as shown in Figure 5.9. In the initial promising region, assignment of links to the first beat was kept fixed, and that to the second and third beats was varied. The initial promising region consisted of three beats where the first beat was composed of links 1 through 10, while the second and third beats could have been composed of any pairs of links as long as the connectivity among the pairs was maintained. Following the principles of the nested partitions method, the initial promising region was divided into a number of sub-regions, and samples were taken from each of these sub-regions as well as from the region surrounding the initial promising region. What it essentially means is that a number of beat designs were selected for further investigation. The performance of the incident response program adopting each of these beat designs was evaluated for different dispatching policies using the simulation model presented in Chapter 3. Ten simulation runs were made, each for 20 days, with 10 independent random number seeds to incorporate the effect of randomly occurring incidents on time-varying traffic which in turn influences the performance of the incident response program. Total vehicle-hours in the system was estimated with and without the Hoosier Helpers operating. The savings in total vehicle-hours in the system due to the freeway patrol program were used as the measure of effectiveness of the program. The beat design with the highest savings in total vehicle-hours was chosen as the best design. For the case of three vehicles patrolling in the peak period, two sets of beat design evolved as good designs for which the performance measures were quite comparable. These designs are designs 4 and 5, as shown in Figures 5.5 and 5.6 respectively. The savings in total vehicle-hours under different dispatching policies for these two designs are presented in Table 5.1 and in Figure 5.10. As the savings in design 5 is a little higher than that in design 4 for all policies except policy E, the former one was chosen as the recommended beat design for this particular case. However, it can be seen that design 4 is also a competitive design.

Following the similar steps, as described above, beats were designed for a different number of vehicles patrolling in the peak period, off-peak period, and night. The savings in total vehicle-hours under a number of selected good beat designs for these cases are presented in Tables 5.2 through 5.12. The savings in the off-peak period patrol are much lower than those in the peak period patrol as the rate of incident occurrence and traffic volume in the off-peak period are much less than those in the peak period. The savings for the operations at night are negligible as fewer incidents occurring in that period have an insignificant impact on the low volume traffic at night.

5.2.2 Area of Operation

As of now, two vehicles patrol the Borman Expressway in the off-peak period as well as at night. I-65 is not included in the patrol area during these periods because of the perception by INDOT personnel that two vehicles are not enough to cover the entire area. In order to examine the validity of this perception, beats were designed in the present study for patrol operation in the off-peak period. Two cases were considered: one without including I-65 in the patrol area, and the other including I-65 in the patrol area. Three good designs, 1a through 3a, as shown in Figures 5.11 through 5.13, were obtained for the case that did not include I-65 in the patrol area. The savings in total vehicle-hours for these three designs are plotted in Figure 5.14. Although the savings under policy E for all three designs were close to each other, much higher savings were obtained for design 3a under policies A, B, C, and D compared to those in the other two designs. Hence, design 3a was considered to be the best design for the case of two vehicles patrolling during off-peak period and without I-65 in the patrol area. Two good designs, 1b and 2b, as shown in Figures 5.15 and 5.16, were obtained for the case that included I-65 in the patrol area. The savings in total vehicle-hours for both designs are plotted in Figure 5.17. In this case also, the savings under policy E for both designs were close to each other, but much higher savings were obtained for design 1b under policies A, B, C, and D compared to those in design 2b. Hence, design 1b was recommended for this case.

5.2.2.1 Effect of Detection Technology on Decision Regarding Area of Operation

The savings under the best beat design for the case including I-65, as well as that for the case without including I-65, are plotted in Figure 5.18. It can be seen that the savings were higher for policies A, B, and C when I-65 was not included in the patrol area. On the contrary, higher savings were obtained for policies D and E when I-65 was included in the patrol area. It should be noted that automatic detection system is needed to implement policies D and E. Once the automatic detection system is installed, comprehensive information about all the incidents in the entire patrol area will be available. Hence, the incident response according to priority schemes, based on incident severity and time to respond, as described in Chapter 3, will be more efficient. On the other hand, the implementation of policies A, B, and C does not require an automatic detection system. Information about incidents is less under these policies as they depend on visual detection that is limited by the sight distance of patrolling vehicles. Even if there is scope of a priority based incident response in policy C, it cannot be implemented effectively as the information about all the incidents in the entire patrolling area would not be known at the time of making the decision regarding which incident to respond. Thus, it is better to patrol a smaller area when an automatic detection system is not installed. This confirms the perception of the INDOT personnel that two vehicles are not enough to cover the entire area including I-65. However, a better job can be done with the same number of vehicles by including I-65 when more information is available about what is going on in the entire patrol area. This establishes the need for an automatic detection system in enhancing the efficiency of an incident management program.

5.2.3 Hours of Operation

It is important to decide how many vehicles should be patrolling in which period as the savings in total vehicle-hours due to incident response vary significantly with the period of operation. A vehicle cannot be used for 24 hours in a day as it needs routine maintenance and normal upkeep. Sometimes even a major repair is needed. It was estimated that on the average a vehicle could be effectively used for approximately eight hours a day. There are several possible ways in which a different number of vehicles from a fixed fleet size can be deployed in different periods. All the possible combinations for fleets of seven, eight, nine, and ten vehicles are listed in Tables 5.13, 5.14, 5.15, and 5.16, respectively. As it can be expected, the savings in the peak period are much higher than those in the off-peak period, as shown in Figure 5.19. It can also be seen from Tables 5.10 through 5.12 that savings at night are negligible compared to those in the peak and off-peak periods. From these observations it may appear that it is a good idea to deploy as many vehicles as possible in the peak period. The highest possible savings for a different number of vehicles patrolling in the peak period are plotted in Figure 5.20. Although the savings under different policies increase with the increasing number of vehicles, the additional increase in savings is not much when the number of vehicles is increased from five to six. This means that five vehicles are enough to cover the given patrol area during the peak period. A similar trend is observed for the patrol operation in the off-peak period. It can be noticed from Figure 5.21 that four vehicles would be sufficient to cover the given patrol area in the off-peak period; the addition of the fifth vehicle may not be necessary.

On the basis of the above observations, it becomes obvious that for the given patrol area one need not look for combinations with more than five and six response vehicles patrolling in the off-peak and peak periods, respectively. Furthermore, the entire night patrol service can be discarded, as savings during that period are negligible. The provision of night patrol service, however, can be justified for social and other issues.

5.2.3.1 Hours of Operation with Different Fleet Sizes

The savings under potential good combinations with a fleet size of seven, eight, nine, and ten response vehicles are presented in Tables 5.17, 5.18, 5.19, and 5.20, respectively. When the fleet size is seven, the highest savings for policy A was obtained with five vehicles patrolling in the peak period and two vehicles patrolling in the off-peak period and I-65 not being included in the patrol area. The same deployment schedule with I-65 being included in the patrol area produced the highest savings for policies D and E. However, the highest savings for policies B and C were recorded for a different deployment schedule of four and three vehicles patrolling the entire area in the peak and off-peak period, respectively. The savings under these deployment schedules are also plotted in Figure 5.22. As it can be observed from Table 5.18, the best schedule for a fleet size of eight was to deploy five vehicles in the peak period and three vehicles in the off-peak period. It can also be noticed from Figure 5.19 that the highest savings for all the policies were obtained for a fleet size of nine by deploying five vehicles in the peak period and four vehicles in the off-peak period. For a fleet size of ten, two deployment schedules had savings close to each other, as can be seen from Table 5.20. One schedule had five vehicles patrolling in both the peak and off-peak periods, and the other had six and four vehicles patrolling in the peak and off-peak periods, respectively. Either of these two schedules may be chosen.

5.2.4 Dispatching Policies

There is a possibility of using different dispatching policies to make a decision regarding which incident to serve first. While policies A, B, and C are based on visual detection by roving response vehicles, policies D and E can be implemented only if an automatic incident detection system is installed. The detailed description of these policies is given in Chapter 3. It is important to verify whether the performance of the incident response program depends on a particular dispatching policy used. If the performance is policy dependent, it is needed to determine which one is the best policy.

The savings in total vehicle-hours with the best possible beat designs and deployment schedules under all the five policies are presented in Table 5.21 and Figure 5.23. It can be observed that higher savings were obtained for incident response operation under policies D and E compared to those under policies A, B, and C, for all the different fleet sizes. It is also interesting to note that the lowest amount of savings was obtained for operation under policy A, and the highest amount of savings was obtained for operation under policy E. Both t-tests and Wilcoxon signed rank tests were conducted for the best deployment schedules with the best possible beat designs for several fleet sizes to check whether the performance under different dispatching policies vary significantly. The results of these tests are summarized in Tables 5.22 through 5.27. It can be observed that there was no statistically significant difference between average savings under policy B and that under policy C. It can also be seen that savings under policy B were significantly higher than those under policy A for all the cases. Thus, among policies A, B, and C, which do not require any automatic detection system, either policy B or C may be chosen. The implementation of policy C needs an extra level of decision making about the severity of incidents. Therefore, considering the ease of implementation, policy B would be preferred to policy C. The savings under policy E were significantly higher than those under policies B and D. Thus, it may be concluded that once an automatic incident detection system is installed, the best performance for the incident response operation can be obtained by adopting policy E.

5.2.5 Fleet Size

As one may intuitively perceive, the performance of an incident response operation varies with the number of response vehicles. The larger the fleet size is, the smaller the beat size and the quicker the incident detection and response time, resulting in better performance. It can be noted from Figure 5.24 that the larger the fleet size is, the higher the savings in total vehicle-hours, as expected. However, the rate of increase in savings with the increasing number of vehicles does not remain the same. It can be observed from Table 5.28 and Figure 5.25 that the increase in savings with the increase in fleet size varies significantly with different levels of fleet size. It also varies across different policies. The highest increase in savings was observed for policies A, B, and C when the fleet size was increased from seven to eight, and the highest increase in savings for policies D and E was obtained by increasing the fleet size from eight to nine.

While a larger fleet adds benefit by increasing savings in total vehicle-hours, it also adds to the cost. Thus, it is necessary to do a trade-off analysis by calculating the marginal benefit-cost ratios. It was estimated using the figures from Latoski et al. (1997) that the annual equivalent cost of adding a response vehicle was approximately $90,170. The annual benefits were obtained by converting the savings in total vehicle-hours in one year into dollars using a value of $14.20 for a vehicle-hour saved (Latoski et al., 1997). Finally, the marginal benefit-cost ratios were estimated, which are presented in Table 5.29 and Figure 5.26. As long as the ratio of marginal savings to marginal cost is above a positive threshold value, it may be desirable to add to the fleet size. Assuming a conservative value of 2 as the threshold value, it would be cost-effective to increase the fleet size from seven to eight if policy A were adopted. But an increase in fleet size from eight to nine would not be economically justifiable. However, it would be cost-effective to maintain a fleet size of nine if policies B and C were used. On the other hand, it would be better not to increase the fleet size from seven if either policy D or E were being implemented.

5.2.6 Existing Operation vs. Improved Operation

As the Hoosier Helper program operates currently, three response vehicles cover the entire patrol area in the peak period, while two vehicles patrol in the off-peak period as well as at night. I-65 is not covered in the off-peak period and at night. The current beat designs for different periods of operation are presented in Table 5.30. Although policy B is followed now, the savings under other policies were also estimated. These savings are presented in Table 5.30. The proposed methodology was used to identify whether a better performance can be obtained with the same fleet size with the adoption of a different deployment schedule and a different beat design.

5.2.6.1 Possible Improvements without Additional Resources

At first, it was checked whether it is possible to improve the effectiveness of the program by modifying the beat design, while keeping the same deployment schedule that is being followed currently. The modified beat design is presented in Table 5.31. It can be observed from Figure 5.27 that a significant amount of vehicle-hours can be saved by modifying the beat design. It was also verified if the program can be further improved by modifying deployment schedules. Two deployment schedules were considered that would maximize the savings in vehicle-hours under policies B and E: one with four and three vehicles deployed in the peak and off-peak period respectively, and the other with five and two vehicles depoyed in the peak and off-peak period respectively. The corresponding beat designs are presented in Table 5.31. Although night patrol did not yield much savings, as discussed in Section 5.2.3, the possibility of deploying one vehicle during the night was explored, considering safety and social isuues. The deployment schedule and beat design for this case are also presented in Table 5.31. The savings for the three above-mentioned cases are plotted in Figure 5.27. It can be clearly observed that savings in total vehicle-hours can be increased significantly for all dispatching policies by modifying the beat design and deployment schedule, while keeping the fleet size the same as it is now. It is also interesting to note that the savings were considerably less for the case where night patrol was provided, compared to the cases that did not provide night patrol. The difference was approximately 40,000 vehicle-hours for a period of 200 days.

5.3 Overall Recommendations

As can be observed from the results presented in the Section 5.2.4, policy E is the best policy to adopt when an automatic incident detection system is available, as the highest savings were obtained for incident response under this policy. However, in many cases such a detection system may not be available and the response vehicles will have to rely on visual detection. Under latter circumstances, policy B would be most suitable. It can be further noticed from the results in the Section 5.2.5 that the cost-effective fleet size under policy E would be seven, while that under policy B would be nine. The cost of two additional response vehicles could have been saved if an automatic detection system were available. Moreover, savings under policy E with seven response vehicles was higher than savings under policy B with even ten vehicles. Hence, one may consider installing an automatic incident detection system provided the cost is less than the enhanced savings due to such a detection system.

The hours of operation and beat designs are extremely important for efficient operation of the incident response program. When policy B is implemented, the optimal fleet size is nine, and five vehicles should be deployed in the peak-period and four vehicles should be deployed in the off-peak period. The beat designs are presented in Table 5.32. When policy E is implemented, the optimal fleet size is seven, and five vehicles should be deployed in the peak-period and two vehicles should be deployed in the off-peak period. The design of five beats in the peak period would be the same as before. The first and second beats in the off-peak period should consist of links 1 through 12 and links 13 through 30 respectively, as presented in Table 5.32. It is not economical, in terms of savings in vehicle-hours, to deploy vehicles in the night, as it can be observed from the figures of savings during the night presented in Tables 5.10 through 5.12. However, considering safety and social issues, one vehicle may be deployed to patrol the freeway and assist stranded motorists during that period.

Table 5.1: Savings in Total Vehicle-Hours in 200 Days for a Set of Good Beat Designs with 3 Vehicles Patrolling in the Peak Period (6AM-10AM & 3PM-7PM)

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
1*	Beat 1: Links 1-12 Beat 2: Links 13-16 & 21-26 Beat 3: Links 17-20 & 27-30	1124234 (1.38%)	1167543 (5.29%)	1167541 (5.29%)	1181182 (6.52%)	1218401 (9.87%)
2	Beat 1: Links 1-10 Beat 2: Links 11-16 & 21-26 Beat 3: Links 17-20 & 27-30	1108918 (0.00%)	1162382 (4.82%)	1162378 (4.82%)	1175959 (6.05%)	1225207 (10.5%)

Note:

- Minimum Savings = 1,108,918 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.2: Savings in Total Vehicle-Hours in 200 Days for a Set of Good Beat Designs with 4 Vehicles Patrolling in the Peak Period (6AM-10AM & 3PM-7PM)

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
1*	Beat 1: Links 1-8 Beat 2: Links 9-14 Beat 3: Links 15-16 & 21-26 Beat 4: Links 17-20 & 27-30	1151335 (0.92%)	1189956 (4.30%)	1189563 (4.27%)	1194409 (4.70%)	1236776 (8.41%)
2	Beat 1: Links 1-8 Beat 2: Links 9-12 Beat 3: Links 13-16 & 21-26 Beat 4: Links 17-20 & 27-30	1142691 (0.16%)	1178905 (3.34%)	1177982 (3.26%)	1196079 (4.84%)	1236925 (8.42%)
3	Beat 1: Links 1-6 Beat 2: Links 7-12 Beat 3: Links 13-16 & 21-26 Beat 4: Links 17-20 & 27-30	1140844 (0.00%)	1178262 (3.28%)	1177664 (3.23%)	1193067 (4.58%)	1238125 (8.53%)

Note:
- Minimum Savings = 1,140,844 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.3: Savings in Total Vehicle-Hours in 200 Days for a Set of Good Beat Designs with 5 Vehicles Patrolling in the Peak Period (6AM-10AM & 3PM-7PM)

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
1*	Beat 1: Links 1-6 Beat 2: Links 7-12 Beat 3: Links 13-16 & 21-26 Beat 4: Links 17-18 & 27-30 Beat 5: Links 19-20	1200262 (0.00%)	1208215 (0.66%)	1207614 (0.61%)	1225688 (2.12%)	1266212 (5.49%)
2	Beat 1: Links 1-8 Beat 2: Links 9-12 Beat 3: Links 13-16 & 21-26 Beat 4: Links 17-18 & 27-30 Beat 5: Links 19-20	1202110 (0.15%)	1208861 (0.72%)	1207933 (0.64%)	1224675 (2.03%)	1263568 (5.27%)

Note:
- Minimum Savings = 1,200,262 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.4: Savings in Total Vehicle-Hours in 200 Days for the Best Beat Design with 6 Vehicles Patrolling in the Peak Period (6AM-10AM & 3PM-7PM)

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
1*	Beat 1: Links 1-4 Beat 2: Links 5-10 Beat 3: Links 11-12 Beat 4: Links 13-16 & 21-26 Beat 5: Links 17-18 & 27-30 Beat 6: Links 19-20	1205709 (0.00%)	1212489 (0.56%)	1211966 (0.52%)	1228753 (1.91%)	1265584 (4.97%)

Note:
- Minimum Savings = 1,205,709 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.5: Savings in Total Vehicle-Hours in 200 Days for a Set of Good Beat Designs while 2 Vehicles are Patrolling in the Off-Peak Period (10AM-3PM & 7PM-10PM) and I-65 is Not Included in the Response Area

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
1*	Beat 1: Links 1-14 Beat 2: Links 15-20	508831 (442%)	513565 (447%)	513587 (447%)	517361 (451%)	512897 (446%)
2	Beat 1: Links 1-12 Beat 2: Links 13-20	95540 (1.69%)	357089 (280%)	357106 (280%)	457714 (387%)	514473 (448%)
3	Beat 1: Links 1-10 Beat 2: Links 11-20	93950 (0.00%)	337253 (259%)	337166 (259%)	450155 (379%)	516154 (449%)

Note:

- Minimum Savings = 93,950 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.6: Savings in Total Vehicle-Hours in 200 Days for a Set of Good Beat Designs while 2 Vehicles are Patrolling in the Off-Peak Period (10AM-3PM & 7PM-10PM) and I-65 is Included in the Response Area

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
1*	Beat 1: Links 1-12 Beat 2: Links 13-20 & 21-30	473657 (382%)	505313 (414%)	505341 (414%)	549899 (459%)	550715 (460%)
2	Beat 1: Links 1-14 Beat 2: Links 15-20 & 21-30	98369 (0%)	306447 (212%)	306465 (212%)	406437 (313%)	548340 (457%)

Note:
- Minimum Savings = 98,369 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.7: Savings in Total Vehicle-Hours in 200 Days for a Set of Good Beat Designs with 3 Vehicles Patrolling in the Off-Peak Period (10AM-3PM & 7PM-10PM)

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
1*	Beat 1: Links 1-14 Beat 2: Links 15-20 Beat 3: Links 21-30	540895 (40.7%)	550326 (43.1%)	550346 (43.1%)	554386 (44.2%)	554392 (44.2%)
2	Beat 1: Links 1-12 Beat 2: Links 13-16 & 21-26 Beat 3: Links 17-20 & 27-30	388957 (1.16%)	426448 (10.9%)	426467 (10.9%)	453129 (17.8%)	557555 (45.0%)
3	Beat 1: Links 1-10 Beat 2: Links 11-16 & 21-26 Beat 3: Links 17-20 & 27-30	384508 (0.00%)	425249 (10.6%)	425258 (10.6%)	457841 (19.1%)	557719 (45.0%)

Note:

- Minimum Savings = 384,508 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.8: Savings in Total Vehicle-Hours in 200 Days for a Set of Good Beat Designs with 4 Vehicles Patrolling in the Off-Peak Period (10AM-3PM & 7PM-10PM)

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy A	B	C	D	E
1*	Beat 1: Links 1-8 Beat 2: Links 9-12 Beat 3: Links 13-16 & 21-30 Beat 4: Links 17-20	547357 (0.00055 %)	558964 (2.12%)	558938 (2.12%)	561512 (2.59%)	561173 (2.52%)
2	Beat 1: Links 1-10 Beat 2: Links 11-12 Beat 3: Links 13-16 & 21-30 Beat 4: Links 17-20	547354 (0.00%)	558858 (2.10%)	558872 (2.10%)	561550 (2.59%)	561031 (2.50%)
3	Beat 1: Links 1-4 Beat 2: Links 5-12 Beat 3: Links 13-16 & 21-30 Beat 4: Links 17-20	547505 (0.03%)	558815 (2.09%)	558841 (2.10%)	561143 (2.52%)	561095 (2.51%)

Note:
- Minimum Savings = 547,354 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.9: Savings in Total Vehicle-Hours in 200 Days for a Set of Good Beat Designs with 5 Vehicles Patrolling in the Off-Peak Period (10AM-3PM & 7PM-10PM)

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
1*	Beat 1: Links 1-6 Beat 2: Links 7-12 Beat 3: Links 13-16 Beat 4: Links 17-20 Beat 5: Links 21-30	553045 (2.02%)	559758 (3.26%)	559736 (3.25%)	560399 (3.37%)	564601 (4.15%)
2	Beat 1: Links 1-6 Beat 2: Links 7-10 Beat 3: Links 11-14 Beat 4: Links 15-16 & 21-30 Beat 5: Links 17-20	542767 (0.12%)	555301 (2.43%)	555291 (2.43%)	556232 (2.61%)	562413 (3.75%)
3	Beat 1: Links 1-6 Beat 2: Links 7-12 Beat 3: Links 13-14 Beat 4: Links 15-16 & 21-30 Beat 5: Links 17-20	542107 (0.00%)	555069 (2.39%)	555048 (2.39%)	556215 (2.60%)	562573 (3.78%)

Note:
- Minimum Savings = 542,107 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.10: Savings in Total Vehicle-Hours in 200 Days for a Set of Good Beat Designs while 2 Vehicles are Patrolling at Night (10PM-6AM) and I-65 is Not Included in the Response Area

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
1*	Beat 1: Links 1-14 Beat 2: Links 15-20	2531 (570%)	2992 (692%)	2993 (692%)	2989 (691%)	2239 (492%)
2	Beat 1: Links 1-12 Beat 2: Links 13-20	411 (8.73%)	845 (124%)	388 (2.65%)	455 (20.4%)	454 (20.1%)
3	Beat 1: Links 1-10 Beat 2: Links 11-20	378 (0.00%)	408 (7.94%)	410 (8.47%)	424 (12.2%)	449 (18.8%)

Note:

- Minimum Savings = 378 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.11: Savings in Total Vehicle-Hours in 200 Days for a Set of Good Beat Designs while 2 Vehicles are Patrolling at Night (10PM-6AM) and I-65 is Included in the Response Area

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
1*	Beat 1: Links 1-14 Beat 2: Links 15-20 & 21-30	210 (14.1%)	331 (79.9%)	331 (79.9%)	423 (130%)	2592 (1309%)
2	Beat 1: Links 1-12 Beat 2: Links 13-20 & 21-30	184 (0.0%)	203 (10.3%)	200 (8.7%)	441 (140%)	460 (150%)

Note:

- Minimum Savings = 184 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.12: Savings in Total Vehicle-Hours in 200 Days for a Set of Good Beat Designs with 3 Vehicles Patrolling at Night (10PM-6AM)

ID No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
1*	Beat 1: Links 1-12 Beat 2: Links 13-16 & 21-26 Beat 3: Links 17-20 & 27-30	1737 (19.2%)	1745 (19.8%)	2600 (78.4%)	2189 (50.2%)	2361 (62.0%)
2	Beat 1: Links 1-10 Beat 2: Links 11-16 & 21-26 Beat 3: Links 17-20 & 27-30	1733 (18.9%)	1743 (19.6%)	2598 (78.3%)	2181 (49.7%)	2365 (62.3%)
3	Beat 1: Links 1-10 Beat 2: Links 11-16 Beat 3: Links 17-20 & 21-30	1486 (1.99%)	1457 (0.00%)	1856 (27.4%)	1944 (33.4%)	2366 (62.4%)

Note:
- Minimum Savings = 1,457 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.13: Possible Combinations of Hours of Operation with a Fleet Size of 7

Combination Number	No. of Vehicles in Peak Period (6-10AM & 3-7PM)	No. of Vehicles in Off-peak Period (10AM-3PM & 7-10PM)	No. of Vehicles in Night Time (10PM-6AM)
1	7	-	-
2	4	3	-
3	5	2	-
4	6	1	-
5	3	2	2
6	5	1	1
7	3	3	1
8	4	2	1

Table 5.14: Possible Combinations of Hours of Operation with a Fleet Size of 8

Combination Number	No. of Vehicles in Peak Period (6-10AM & 3-7PM)	No. of Vehicles in Off-peak Period (10AM-3PM & 7-10PM)	No. of Vehicles in Night Time (10PM-6AM)
1	8	-	-
2	4	4	-
3	5	3	-
4	6	2	-
5	7	1	-
6	4	2	2
7	3	3	2
8	6	1	1
9	4	3	1
10	5	2	1

Table 5.15: Possible Combinations of Hours of Operation with a Fleet Size of 9

Combination Number	No. of Vehicles in Peak Period (6-10AM & 3-7PM)	No. of Vehicles in Off-peak Period (10AM-3PM & 7-10PM)	No. of Vehicles in Night Time (10PM-6AM)
1	9	-	-
2	5	4	-
3	6	3	-
4	7	2	-
5	8	1	-
6	3	3	3
7	5	2	2
8	4	3	2
9	7	1	1
10	4	4	1
11	5	3	1

Table 5.16: Possible Combinations of Hours of Operation with a Fleet Size of 10

Combination Number	No. of Vehicles in Peak Period (6-10AM & 3-7PM)	No. of Vehicles in Off-peak Period (10AM-3PM & 7-10PM)	No. of Vehicles in Night Time (10PM-6AM)
1	10	-	-
2	5	5	-
3	6	4	-
4	7	3	-
5	8	2	-
6	9	1	-
7	4	3	3
8	6	2	2
9	4	4	2
10	5	3	2
11	8	1	1
12	5	4	1
13	6	3	1
14	7	2	1

Table 5.17: Savings in Total Vehicle-Hours in 200 Days with Different Combinations of Hours of Operation with a Fleet Size of 7

Combina-tion No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
2	Peak: 4 Off-Peak: 3 Night: 0	1692230 (5.89%)	1740282 (8.90%)	1739909 (8.87%)	1748795 (9.43%)	1791168 (12.1%)
3	Peak: 5 Off-Peak: 2 (I-65 Not Included) Night: 0	1709093 (6.95%)	1721780 (7.74%)	1721201 (7.70%)	1743049 (9.07%)	1779109 (11.3%)
	Peak: 5 Off-Peak: 2 (I-65 Included) Night: 0	1673919 (4.74%)	1713528 (7.22%)	1712955 (7.19%)	1775587 (11.1%)	1816927 (13.7%)
5	Peak: 3 Off-Peak: 2 (I-65 Not Included) Night: 2	1635596 (2.35%)	1684100 (5.38%)	1684121 (5.38%)	1701532 (6.47%)	1733537 (8.47%)
	Peak: 3 Off-Peak: 2 (I-65 Included) Night: 2	1598101 (0.00%)	1673187 (4.70%)	1673213 (4.70%)	1731504 (8.35%)	1771708 (10.9%)

Note:
- Minimum Savings = 1,598,101 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.18: Savings in Total Vehicle-Hours in 200 Days with Different Combinations of Hours of Operation with a Fleet Size of 8

Combina-tion No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
2	Peak: 4 Off-Peak: 4 Night: 0	1698692 (5.51%)	1748920 (8.63%)	1748501 (8.61%)	1755921 (9.07%)	1797949 (11.7%)
3	Peak: 5 Off-Peak: 3 Night: 0	1741157 (8.15%)	1758541 (9.23%)	1757960 (9.20%)	1780074 (10.6%)	1820604 (13.1%)
4	Peak: 6 Off-Peak: 2 (I-65 Not Included) Night: 0	1714540 (6.50%)	1726054 (7.21%)	1725553 (7.18%)	1746114 (8.46%)	1778481 (10.5%)
	Peak: 6 Off-Peak: 2 (I-65 Included) Night: 0	1679366 (4.31%)	1717802 (6.70%)	1717307 (6.67%)	1778652 (10.5%)	1816299 (12.8%)
6	Peak: 4 Off-Peak: 2 (I-65 Not Included) Night: 2 (I-65 Not Included)	1662697 (3.28%)	1706513 (6.00%)	1706143 (5.98%)	1714759 (6.51%)	1751912 (8.82%)
	Peak: 4 Off-Peak: 2 (I-65 Included) Night: 2 (I-65 Included)	1625202 (0.95%)	1695600 (5.32%)	1695235 (5.30%)	1744731 (8.37%)	1790083 (11.2%)

Table 5.18, continued

Combina-tion No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
7	Peak: 3 Off-Peak: 3 Night: 2 (I-65 Not Included)	1612238 (0.14%)	1675622 (4.08%)	1675633 (4.08%)	1635317 (1.58%)	1773953 (10.2%)
	Peak: 3 Off-Peak: 3 Night: 2 (I-65 Included)	1609917 (0.00%)	1672961 (3.92%)	1672971 (3.92%)	1632751 (1.42%)	1774306 (10.2%)

Note:
- Minimum Savings = 1,609,917 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.19: Savings in Total Vehicle-Hours in 200 Days with Different Combinations of Hours of Operation with a Fleet Size of 9

Combination No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
2	Peak: 5 Off-Peak: 4 Night: 0	1747619 (4.84%)	1767179 (6.02%)	1766552 (5.98%)	1787200 (7.22%)	1827385 (9.63%)
3	Peak: 6 Off-Peak: 3 Night: 0	1746604 (4.78%)	1762815 (5.76%)	1762312 (5.73%)	1783139 (6.98%)	1819976 (9.19%)
6	Peak: 3 Off-Peak: 3 Night: 3	1666866 (0.00%)	1719614 (3.16%)	1720487 (3.22%)	1737757 (4.25%)	1775154 (6.50%)
7	Peak: 5 Off-Peak: 2 (I-65 Not Included) Night: 2 (I-65 Not Included)	1711624 (2.69%)	1724772 (3.47%)	1724194 (3.44%)	1746038 (4.75%)	1781348 (6.87%)
	Peak: 5 Off-Peak: 2 (I-65 Included) Night: 2 (I-65 Included)	1674129 (0.44%)	1713859 (2.82%)	1713286 (2.78%)	1776010 (6.55%)	1819519 (9.16%)
8	Peak: 4 Off-Peak: 3 Night: 2 (I-65 Not Included)	1694761 (1.67%)	1743274 (4.58%)	1742902 (4.56%)	1751784 (5.09%)	1793407 (7.59%)
	Peak: 4 Off-Peak: 3 Night: 2 (I-65 Included)	1692440 (1.53%)	1740613 (4.42%)	1740240 (4.40%)	1749218 (4.94%)	1793760 (7.61%)

Table 5.19, continued

Note:
- Minimum Savings = 1,666,866 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.20: Savings in Total Vehicle-Hours in 200 Days with Different Combinations of Hours of Operation with a Fleet Size of 10

Combination No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
2	Peak: 5 Off-Peak: 5 Night: 0	1753307 (4.39%)	1767973 (5.26%)	1767350 (5.23%)	1786087 (6.34%)	1830813 (9.00%)
3	Peak: 6 Off-Peak: 4 Night: 0	1753066 (4.38%)	1771453 (5.47%)	1770904 (5.44%)	1790265 (6.59%)	1826757 (8.76%)
7	Peak: 4 Off-Peak: 3 Night: 3	1693967 (0.86%)	1742027 (3.72%)	1742509 (3.75%)	1750984 (4.25%)	1793529 (6.78%)
8	Peak: 6 Off-Peak: 2 (I-65 Not Included) Night: 2 (I-65 Not Included)	1717071 (2.23%)	1729046 (2.95%)	1728546 (2.92%)	1749103 (4.14%)	1780720 (6.02%)
	Peak: 6 Off-Peak: 2 (I-65 Included) Night: 2 (I-65 Included)	1679576 (0.00%)	1718133 (2.30%)	1717638 (2.27%)	1779075 (5.92%)	1818891 (8.29%)
9	Peak: 4 Off-Peak: 4 Night: 2 (I-65 Not Included)	1701223 (1.29%)	1751912 (4.31%)	1751494 (4.28%)	1758910 (4.72%)	1800188 (7.18%)
	Peak: 4 Off-Peak: 4 Night: 2 (I-65 Included)	1698902 (1.15%)	1749251 (4.15%)	1748832 (4.12%)	1756344 (4.57%)	1800541 (7.20%)

Table 5.20, continued

Combination No.	Beat Design	Savings in Total Vehicle-Hours under Policy				
		A	B	C	D	E
10	Peak: 5 Off-Peak: 3 Night: 2 (I-65 Not Included)	1743688 (3.82%)	1761533 (4.88%)	1760953 (4.85%)	1783063 (6.16%)	1822843 (8.53%)
	Peak: 5 Off-Peak: 3 Night: 2 (I-65 Included)	1741367 (3.68%)	1758872 (4.72%)	1758291 (4.69%)	1780497 (6.01%)	1823196 (8.55%)

Note:
- Minimum Savings = 1,679,576 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.21: Savings in Total Vehicle-Hours in 200 Days under Different Policies

Fleet Size	Savings in Total Vehicle-Hours under Policy				
	A	B	C	D	E
7	1709093 (0.00%)	1740282 (1.82%)	1739909 (1.80%)	1775587 (3.89%)	1816927 (6.31%)
8	1741157 (1.88%)	1758541 (2.89%)	1757960 (2.86%)	1780074 (4.15%)	1820604 (6.52%)
9	1747619 (2.25%)	1767179 (3.40%)	1766552 (3.36%)	1787200 (4.57%)	1827385 (6.92%)
10	1753066 (2.57%)	1771453 (3.65%)	1770904 (3.62%)	1790265 (4.75%)	1830813 (7.12%)

Note:
- Minimum Savings = 1,709,093 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.22: Comparison of Savings under Different Policies with 4 Vehicles Patrolling in the Peak Period and 3 Vehicles Patrolling in the Off-Peak Period

Alternatives	Comparisons	Statistical Tests	Test Statistics	Comment
Policy A vs. Policy B	Comparing Means	t-test	$t^*=1.619$	Mean Savings under Policy B is Higher than That under Policy A at 90% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.09$	Median Savings under Policy B is Higher than That under Policy A at 95% Confidence Level
Policy B vs. Policy C	Comparing Means	t-test	$t^*=0.775$	There is Not Much Difference between Mean Savings under Policy B and That under Policy C at 90% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=0.153$	There is Not Much Difference between Median Savings under Policy B and That under Policy C at 90% Confidence Level
Policy D vs. Policy E	Comparing Means	t-test	$t^*=2.441$	Mean Savings under Policy E is Higher than That under Policy D at 95% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=1.58$	Median Savings under Policy E is Higher than That under Policy D at 90% Confidence Level
Policy B vs. Policy E	Comparing Means	t-test	$t^*=1.954$	Mean Savings under Policy E is Higher than That under Policy B at 95% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.09$	Median Savings under Policy E is Higher than That under Policy B at 95% Confidence Level

Note: One-sided test results are reported in all the cases.

Table 5.23: Comparison of Savings under Different Policies with 5 Vehicles Patrolling in the Peak Period and 2 Vehicles Patrolling in the Off-Peak Period

Alternatives	Comparisons	Statistical Tests	Test Statistics	Comment
Policy A vs. Policy B	Comparing Means	t-test	$t^*=1.546$	Mean Savings under Policy B is Higher than That under Policy A at 90% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=1.682$	Median Savings under Policy B is Higher than That under Policy A at 95% Confidence Level
Policy D vs. Policy E	Comparing Means	t-test	$t^*=2.442$	Mean Savings under Policy E is Higher than That under Policy D at 95% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.293$	Median Savings under Policy E is Higher than That under Policy D at 95% Confidence Level
Policy B vs. Policy E	Comparing Means	t-test	$t^*=2.303$	Mean Savings under Policy E is Higher than That under Policy B at 95% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.191$	Median Savings under Policy E is Higher than That under Policy B at 95% Confidence Level

Note:

- One-sided test results are reported in all the cases.
- Results for policy B are for the case with 4 vehicles patrolling in peak period and 3 vehicles patrolling in off-peak period.
- Results for policy A are obtained with I-65 not being included in the patrol area.
- Results for policies D and E are obtained with I-65 being included in the patrol area.

Table 5.24: Comparison of Savings under Different Policies with 5 Vehicles Patrolling in the Peak Period and 3 Vehicles Patrolling in the Off-Peak Period

Alternatives	Compari-sons	Statistical Tests	Test Statistics	Comment
Policy A vs. Policy B	Comparing Means	t-test	$t^*=2.123$	Mean Savings under Policy B is Higher than That under Policy A at 95% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=1.886$	Median Savings under Policy B is Higher than That under Policy A at 95% Confidence Level
Policy B vs. Policy C	Comparing Means	t-test	$t^*=1.207$	There is Not Much Difference between Mean Savings under Policy B and That under Policy C at 90% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=1.223$	There is Not Much Difference between Median Savings under Policy B and That under Policy C at 90% Confidence Level
Policy D vs. Policy E	Comparing Means	t-test	$t^*=2.263$	Mean Savings under Policy E is Higher than That under Policy D at 95% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.191$	Median Savings under Policy E is Higher than That under Policy D at 95% Confidence Level
Policy B vs. Policy E	Comparing Means	t-test	$t^*=3.008$	Mean Savings under Policy E is Higher than That under Policy B at 99% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.701$	Median Savings under Policy E is Higher than That under Policy B at 99% Confidence Level

Note: One-sided test results are reported in all the cases.

Table 5.25: Comparison of Savings under Different Policies with 5 Vehicles Patrolling in the Peak Period and 4 Vehicles Patrolling in the Off-Peak Period

Alternatives	Comparisons	Statistical Tests	Test Statistics	Comment
Policy A vs. Policy B	Comparing Means	t-test	$t^*=1.873$	Mean Savings under Policy B is Higher than That under Policy A at 95% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=1.988$	Median Savings under Policy B is Higher than That under Policy A at 95% Confidence Level
Policy B vs. Policy C	Comparing Means	t-test	$t^*=1.32$	There is Not Much Difference between Mean Savings under Policy B and That under Policy C at 90% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.197$	Median Savings under Policy B is Higher than That under Policy C at 95% Confidence Level
Policy D vs. Policy E	Comparing Means	t-test	$t^*=2.226$	Mean Savings under Policy E is Higher than That under Policy D at 95% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.701$	Median Savings under Policy E is Higher than That under Policy D at 99% Confidence Level
Policy B vs. Policy E	Comparing Means	t-test	$t^*=2.874$	Mean Savings under Policy E is Higher than That under Policy B at 99% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.803$	Median Savings under Policy E is Higher than That under Policy B at 99% Confidence Level

Note: One-sided test results are reported in all the cases.

Table 5.26: Comparison of Savings under Different Policies with 5 Vehicles Patrolling in the Peak Period and 5 Vehicles Patrolling in the Off-Peak Period

Alternatives	Comparisons	Statistical Tests	Test Statistics	Comment
Policy A vs. Policy B	Comparing Means	t-test	$t^*=1.708$	Mean Savings under Policy B is Higher than That under Policy A at 90% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=1.886$	Median Savings under Policy B is Higher than That under Policy A at 95% Confidence Level
Policy B vs. Policy C	Comparing Means	t-test	$t^*=1.297$	There is Not Much Difference between Mean Savings under Policy B and That under Policy C at 90% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=1.834$	Median Savings under Policy B is Higher than That under Policy C at 95% Confidence Level
Policy D vs. Policy E	Comparing Means	t-test	$t^*=2.481$	Mean Savings under Policy E is Higher than That under Policy D at 95% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.395$	Median Savings under Policy E is Higher than That under Policy D at 99% Confidence Level
Policy B vs. Policy E	Comparing Means	t-test	$t^*=3.101$	Mean Savings under Policy E is Higher than That under Policy B at 99% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.803$	Median Savings under Policy E is Higher than That under Policy B at 99% Confidence Level

Note: One-sided test results are reported in all the cases.

Table 5.27: Comparison of Savings under Different Policies with 6 Vehicles Patrolling in the Peak Period and 4 Vehicles Patrolling in the Off-Peak Period

Alternatives	Comparisons	Statistical Tests	Test Statistics	Comment
Policy A vs. Policy B	Comparing Means	t-test	$t^*=1.692$	Mean Savings under Policy B is Higher than That under Policy A at 90% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=1.784$	Median Savings under Policy B is Higher than That under Policy A at 95% Confidence Level
Policy B vs. Policy C	Comparing Means	t-test	$t^*=1.149$	There is Not Much Difference between Mean Savings under Policy B and That under Policy C at 90% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=1.836$	Median Savings under Policy B is Higher than That under Policy C at 95% Confidence Level
Policy D vs. Policy E	Comparing Means	t-test	$t^*=2.018$	Mean Savings under Policy E is Higher than That under Policy D at 95% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=1.886$	Median Savings under Policy E is Higher than That under Policy D at 95% Confidence Level
Policy B vs. Policy E	Comparing Means	t-test	$t^*=2.612$	Mean Savings under Policy E is Higher than That under Policy B at 95% Confidence Level
	Comparing Medians	Wilcoxon Signed Rank Test	$z^*=2.803$	Median Savings under Policy E is Higher than That under Policy B at 99% Confidence Level

Note: One-sided test results are reported in all the cases.

Table 5.28: Increase in Savings in Total Vehicle-Hours in One Year
by Increasing Fleet Size

Increasing Fleet Size	Savings in Total Vehicle-Hours under Policy				
	A	B	C	D	E
From 7 To 8	58517	33323	32943	8189	6711
From 8 To 9	11793	15764	15680	13005	12375
From 9 To 10	9941	7800	7942	5594	6256

Table 5.29: Effect of Fleet Size on Ratio of Marginal Savings to Marginal Cost

Increasing Fleet Size	Savings in Total Vehicle-Hours under Policy				
	A	B	C	D	E
From 7 To 8	9.22	5.25	5.19	1.29	1.06
From 8 To 9	1.86	2.48	2.47	2.05	1.95
From 9 To 10	1.57	1.23	1.25	0.88	0.99

Table 5.30: Savings in Total Vehicle-Hours in 200 Days with Existing Combination of Hours of Operation and Beat Design with a Fleet Size of 7

Beat Design	Savings in Total Vehicle-Hours under Policy				
	A	B	C	D	E
Peak: 3 Beats Beat 1: Links 1-12 Beat 2: Links 11-20 Beat 3: Links 21-30 Off-Peak: 2 Beats (I-65 Not Included) Beat 1: Links 1-12 Beat 2: Links 11-20 Night: 2 (I-65 Not Included) Beat 1: Links 1-12 Beat 2: Links 11-20	1410002 (0.00%)	1443216 (2.36%)	1442181 (2.28%)	1587720 (12.6%)	1699374 (20.5%)

Note:

- Minimum Savings = 1,410,002 vehicle-hours
- The figures in the parentheses are additional savings over the minimum savings

Table 5.31: Summary of Possible Improvements without Additional Resources

	Deployment Schedule	Beat Design
Existing Operation	3 vehicles in the peak period, 2 vehicles in the off-peak period, and 2 vehicles at night	Peak: 3 Beats Beat 1: Links 1-12 Beat 2: Links 11-20 Beat 3: Links 21-30 Off-Peak: 2 Beats (I-65 Not Included) Beat 1: Links 1-12 Beat 2: Links 11-20 Night: 2 Beats (I-65 Not Included) Beat 1: Links 1-12 Beat 2: Links 11-20
Improved Operation # 1	Same deployment schedule as the existing operation	Peak: 3 Beats Beat 1: Links 1-12, Beat 2: Links 13-16 & 21-26, Beat 3: Links 17-20 & 27-30 Off-Peak: 2 Beats (I-65 Not Included) Beat 1: Links 1-14 Beat 2: Links 15-20 Night: 2 Beats (I-65 Not Included) Beat 1: Links 1-14 Beat 2: Links 15-20
Improved Operation # 2	4 vehicles in peak the period, 2 vehicles in the off-peak period, and 1 vehicle at night	Peak: 4 Beats Beat 1: Links 1-8 Beat 2: Links 9-14, Beat 3: Links 15-16 & 21-26 Beat 4: Links 17-20 & 27-30 Off-Peak: 2 Beats (I-65 Not Included) Beat 1: Links 1-14 Beat 2: Links 15-20 Night: 1 Beat All links are covered by one vehicle

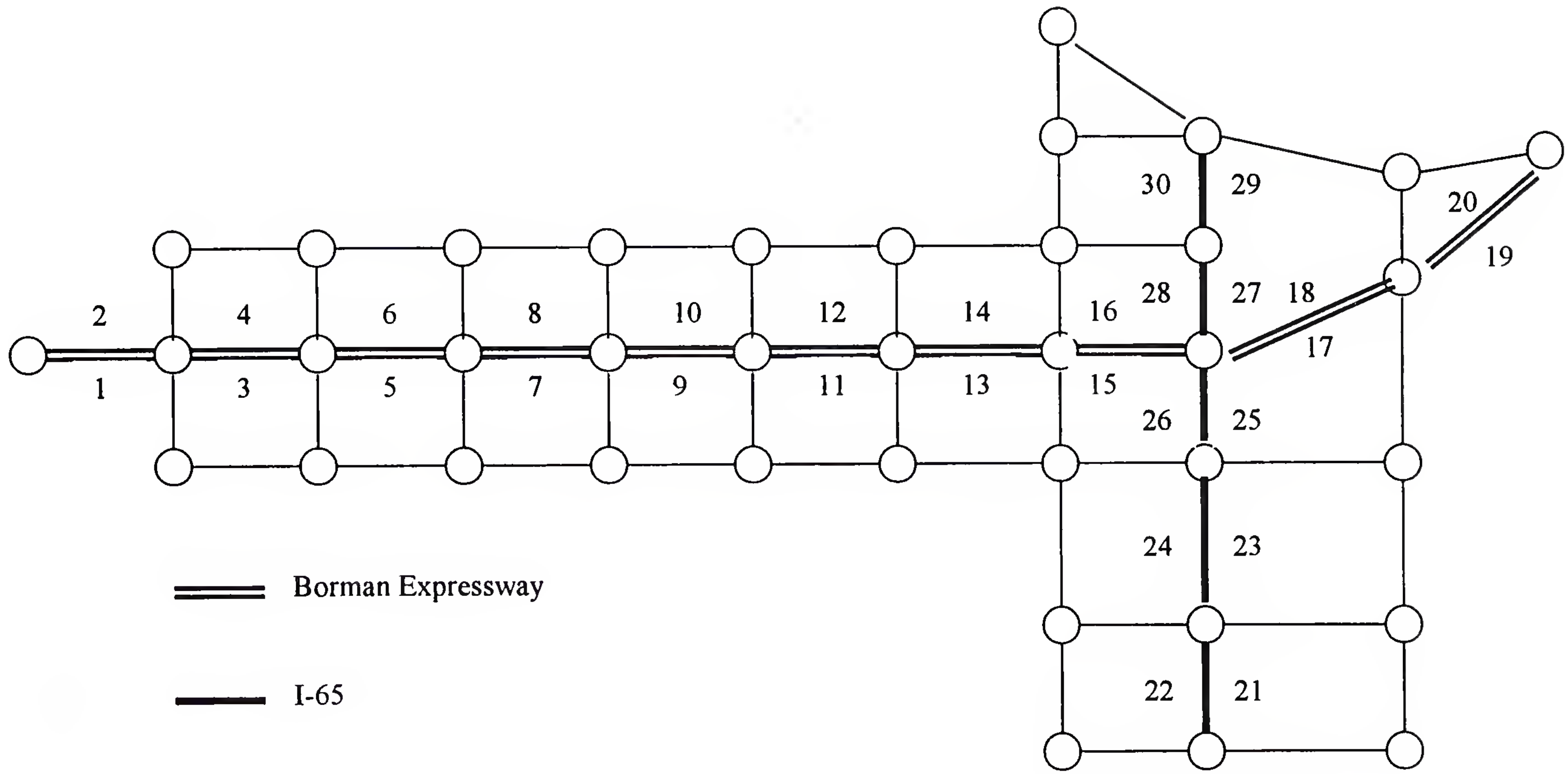
Table 5.31, continued

	Deployment Schedule	Beat Design
Improved Operation # 3	5 vehicles in the peak period, and 2 vehicles in the off-peak period	Peak: 5 Beats Beat 1: Links 1-6 Beat 2: Links 7-12 Beat 3: Links 13-16 & 21-26 Beat 4: Links 17-18 & 27-30 Beat 5: Links 19-20 Off-Peak: 2 Beats (I-65 Not Included) Beat 1: Links 1-14 Beat 2: Links 15-20
Improved Operation # 4	4 vehicles in peak the period, and 3 vehicles in the off-peak period	Peak: 4 Beats Beat 1: Links 1-8 Beat 2: Links 9-14 Beat 3: Links 15-16 & 21-26 Beat 4: Links 17-20 & 27-30 Off-Peak: 3 Beats (I-65 Included) Beat 1: Links 1-14 Beat 2: Links 15-20 Beat 3: Links 21-30

Note: - Fleet size is 7 and dispatching policy is B for all cases

Table 5.32: Summary of Overall Recommendations

	Existing Program	Recommendations without Automatic Detection	Recommendations with Automatic Detection
Fleet Size	7	9	7
Dispatching Policy	B	B	E
Deployment Schedule	3 vehicles in the peak period, 2 vehicles in the off-peak period, and 2 vehicles at night	5 vehicles in the peak period, and 4 vehicles in the off-peak period	5 vehicles in the peak period, and 2 vehicles in the off-peak period
Beat Design	Peak: 3 Beats Beat 1: Links 1-12 Beat 2: Links 11-20 Beat 3: Links 21-30 Off-Peak: 2 Beats (I-65 Not Included) Beat 1: Links 1-12 Beat 2: Links 11-20 Night: 2 (I-65 Not Included) Beat 1: Links 1-12 Beat 2: Links 11-20	Peak: 5 Beats Beat 1: Links 1-6 Beat 2: Links 7-12 Beat 3: Links 13-16 & 21-26 Beat 4: Links 17-18 & 27-30 Beat 5: Links 19-20 Off-Peak: 2 Beats (I-65 Included) Beat 1: Links 1-8 Beat 2: Links 9-12 Beat 3: Links 13-16 & 21-30 Beat 4: Links 17-20	Peak: 5 Beats Beat 1: Links 1-6 Beat 2: Links 7-12 Beat 3: Links 13-16 & 21-26 Beat 4: Links 17-18 & 27-30 Beat 5: Links 19-20 Off-Peak: 2 Beats (I-65 Included) Beat 1: Links 1-12 Beat 2: Links 13-30



Note: Numbering of the links on the Borman Expressway and I-65 is shown in the figure. Links for each direction of travel are numbered separately.

Figure 5.1: Network for the Example Problem

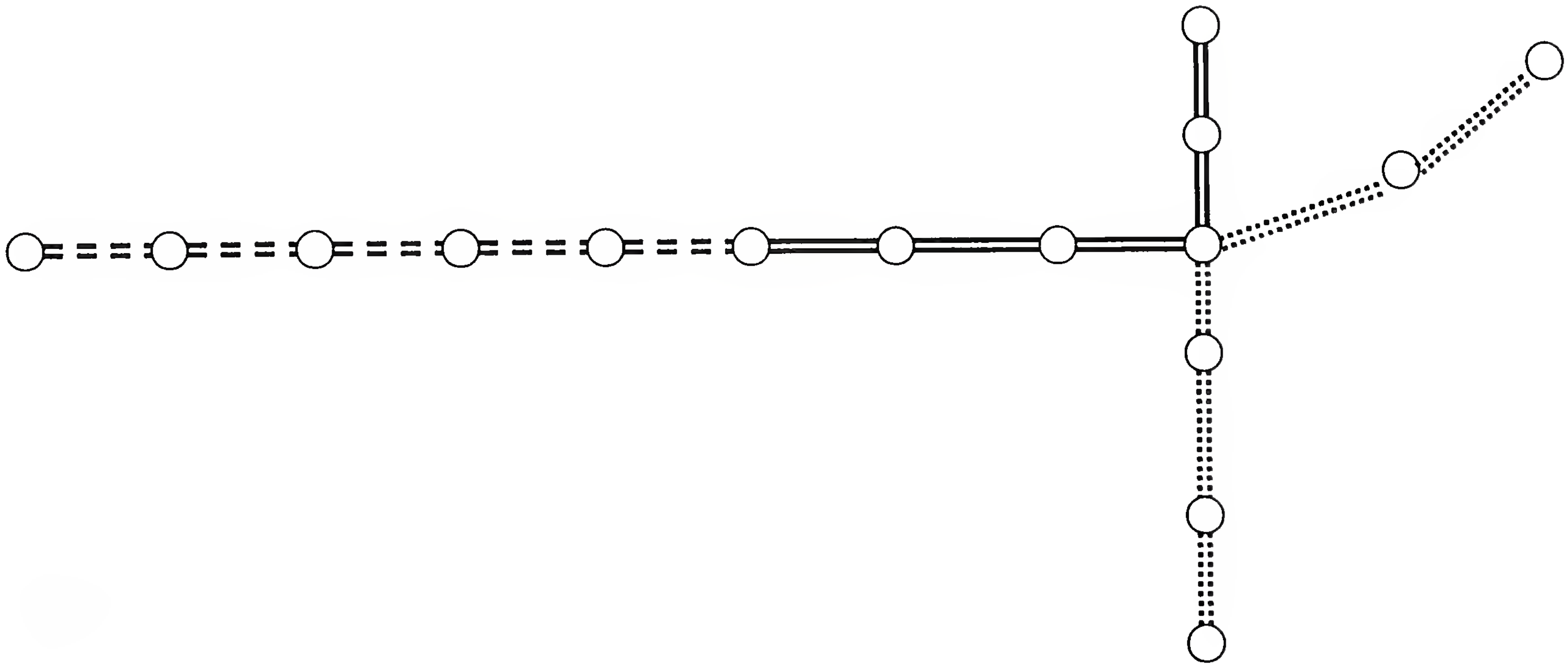


Figure 5.2: Configuration of 3 Beats in Design 1

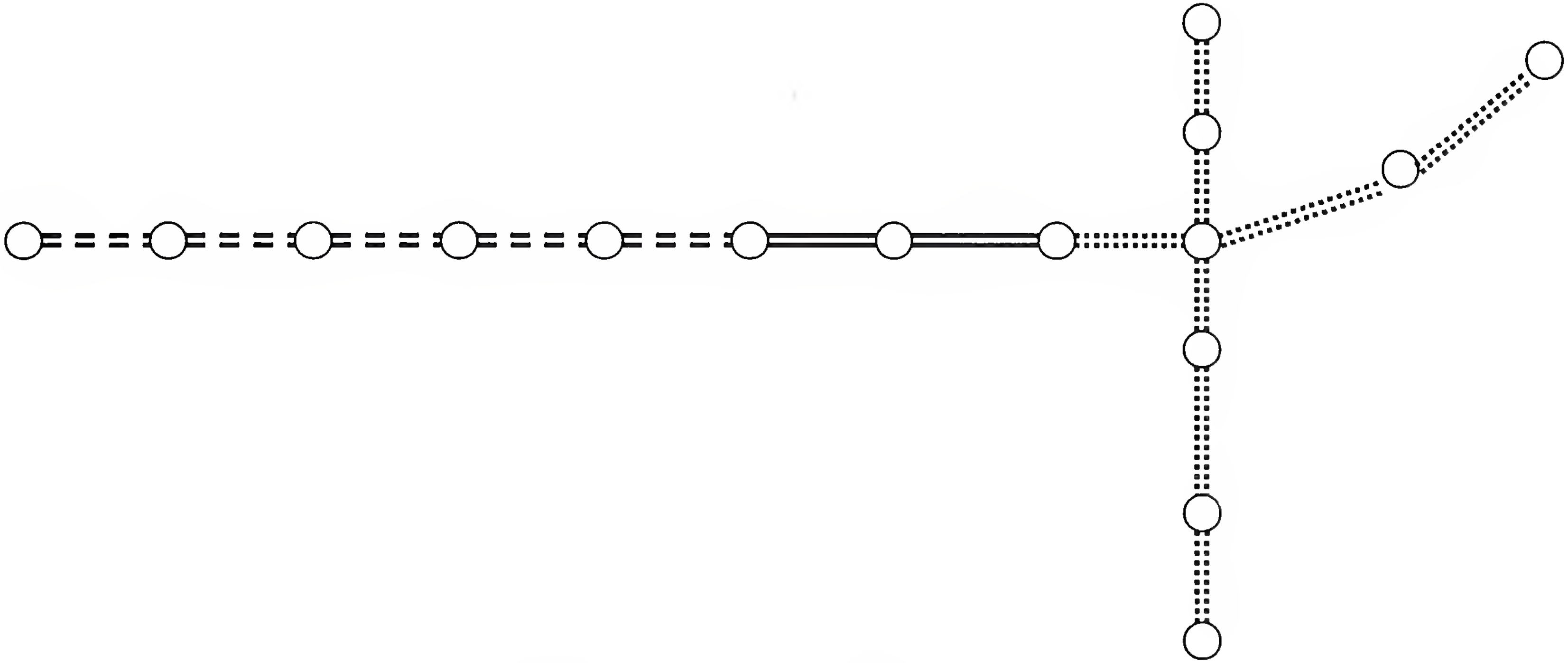


Figure 5.3: Configuration of 3 Beats in Design 2

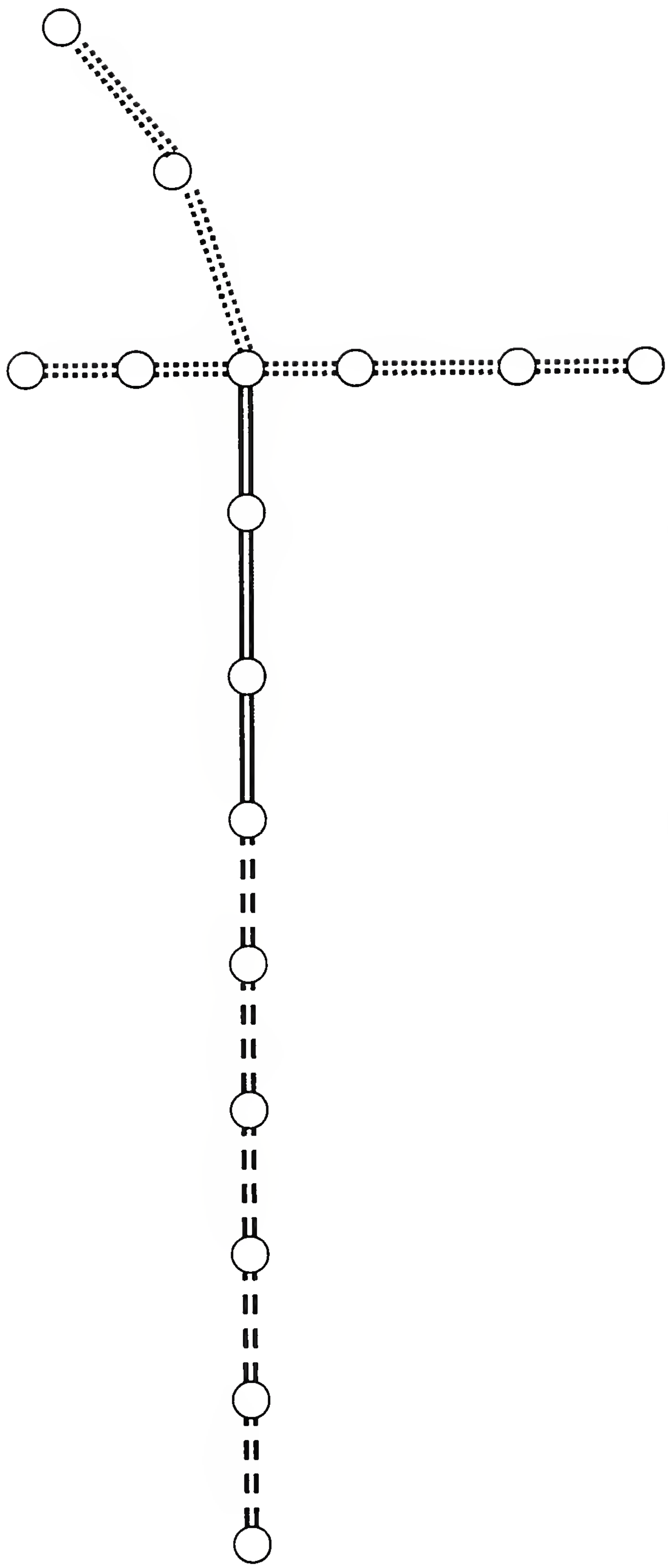


Figure 5.4: Configuration of 3 Beats in Design 3

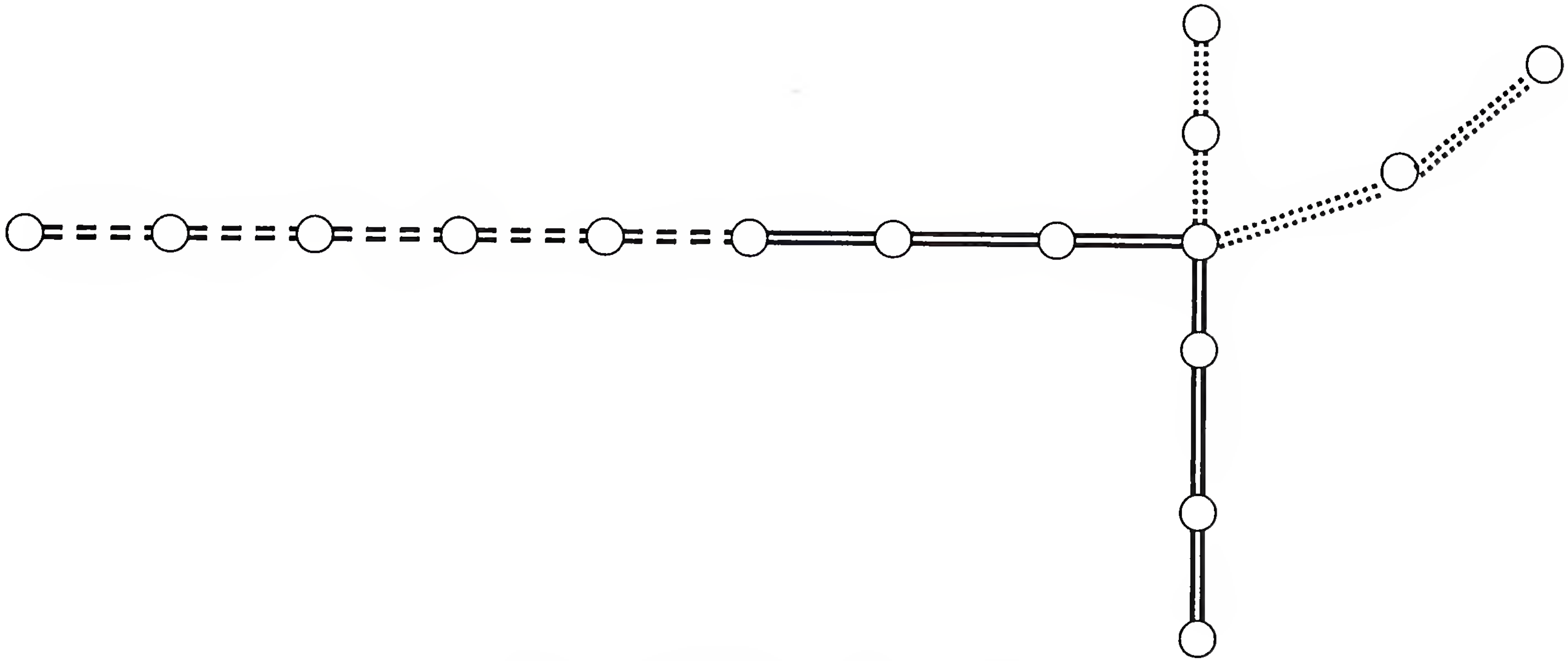


Figure 5.5: Configuration of 3 Beats in Design 4

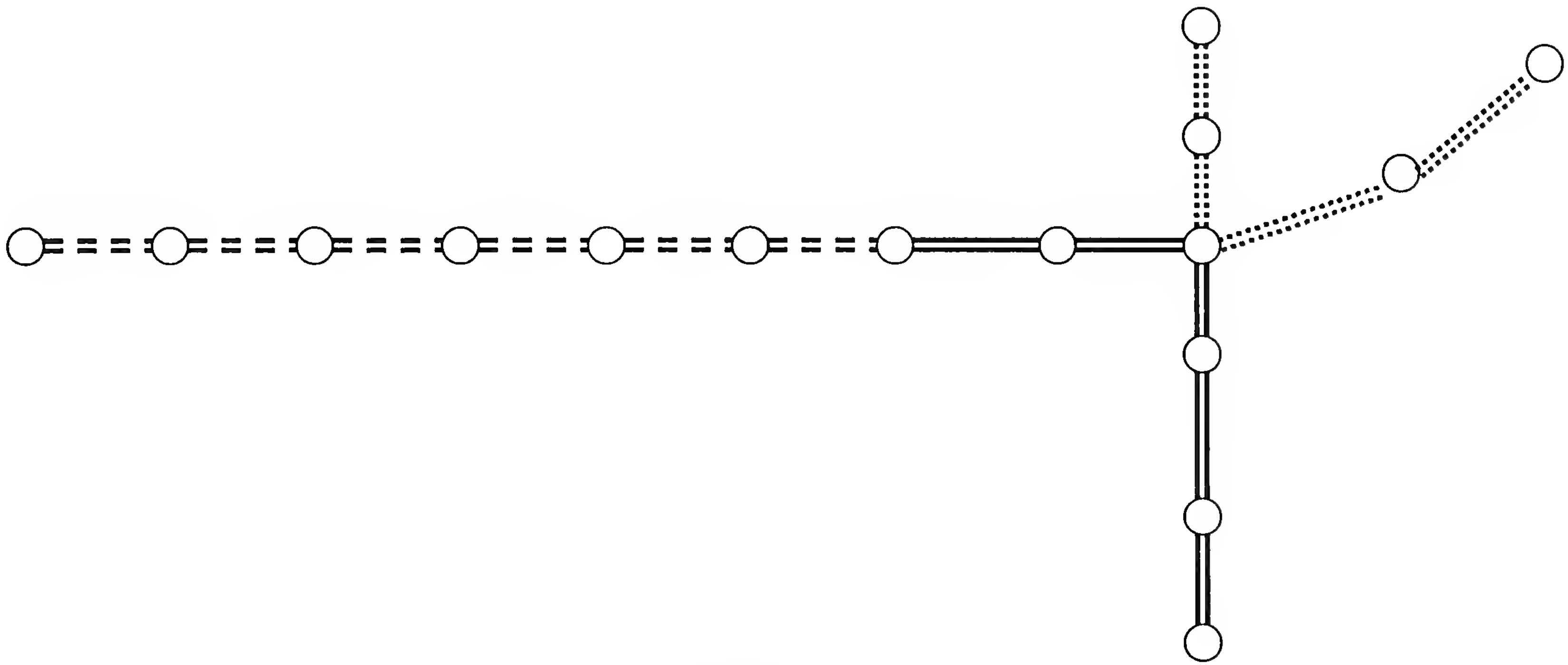


Figure 5.6: Configuration of 3 Beats in Design 5

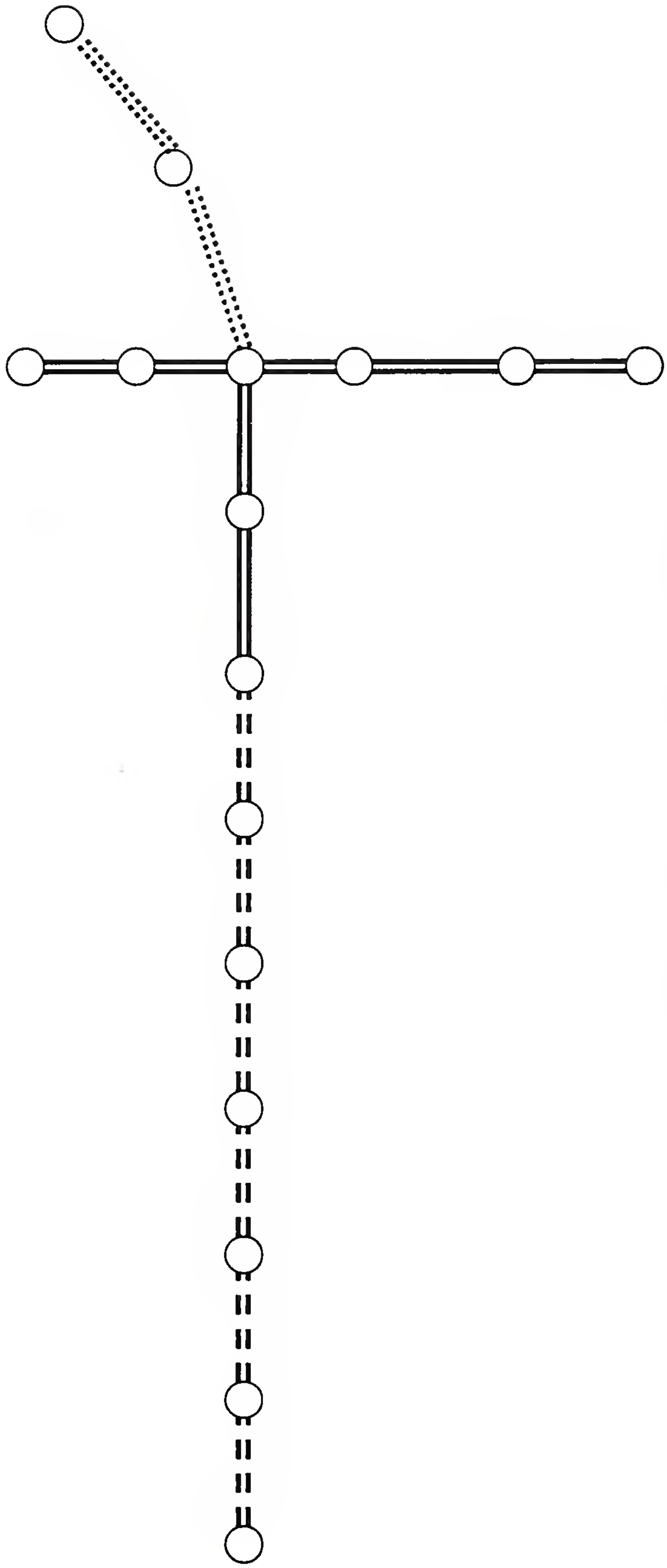


Figure 5.7: Configuration of 3 Beats in Design 6

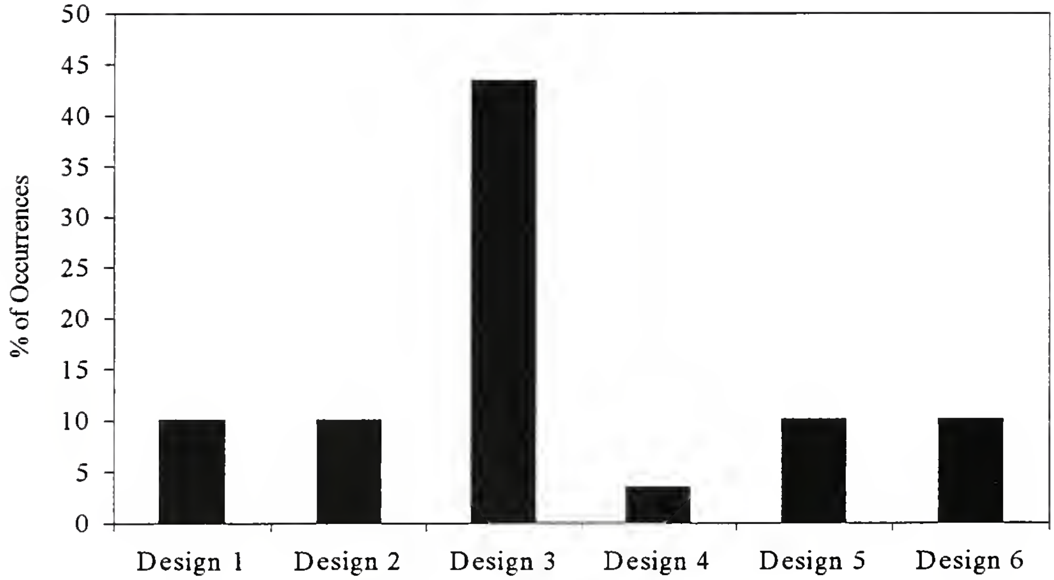


Figure 5.8: Frequently Occurring Beat Designs

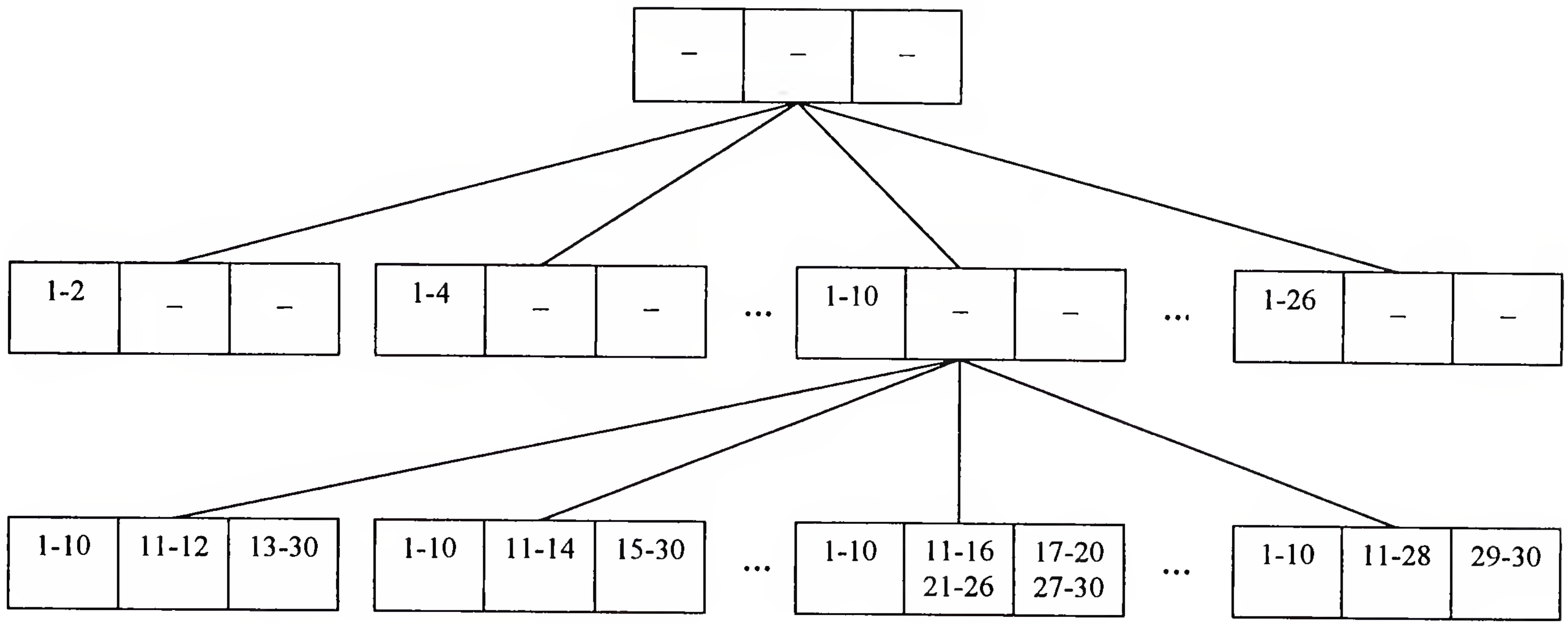


Figure 5.9: Use of the Nested Partitions Method to Find the Optimal Beat Design with 3 Vehicles Patrolling in the Peak Period

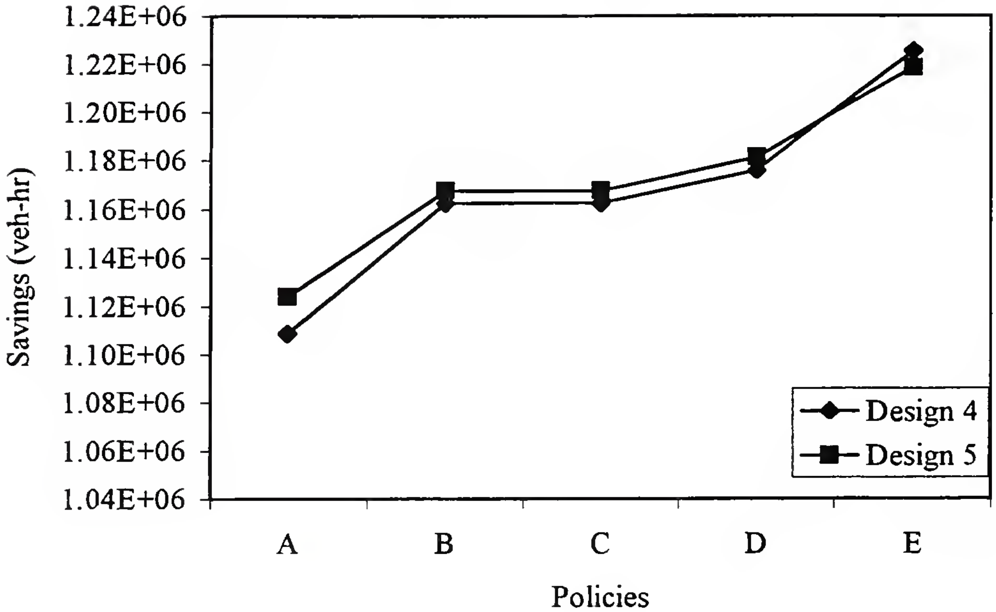


Figure 5.10: Savings in Total Vehicle-Hours in 200 Days due to Incident Response Operation (3 Beats in the Peak Period)

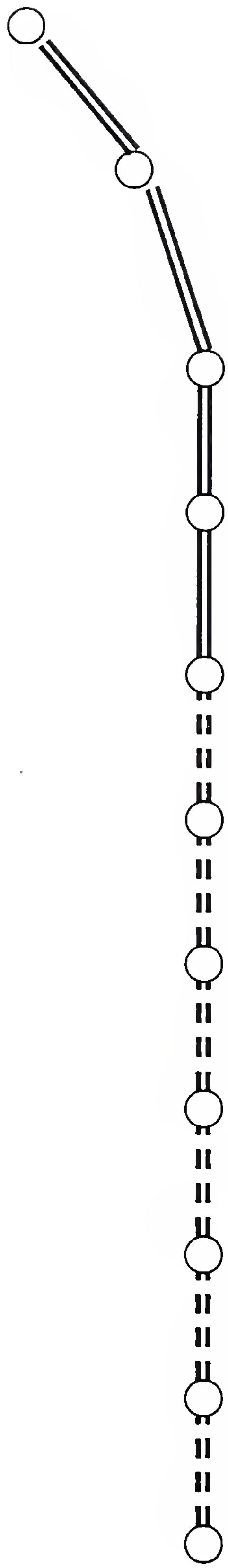


Figure 5.11: Configuration of 2 Beats in Design 1a

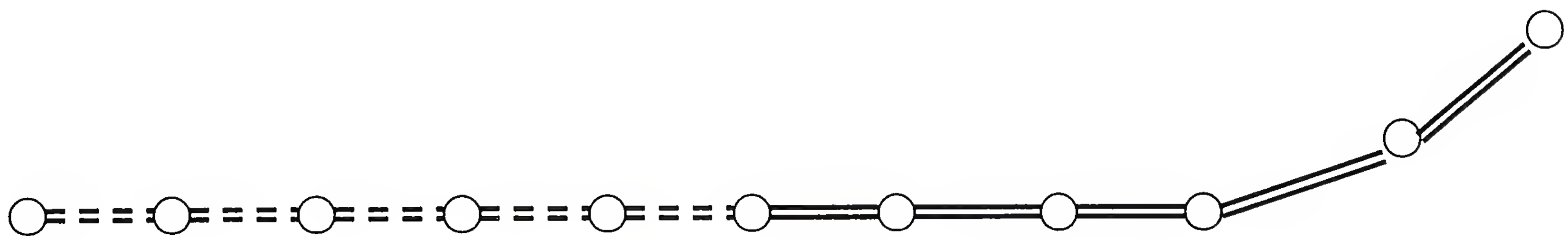


Figure 5.12: Configuration of 2 Beats in Design 2a

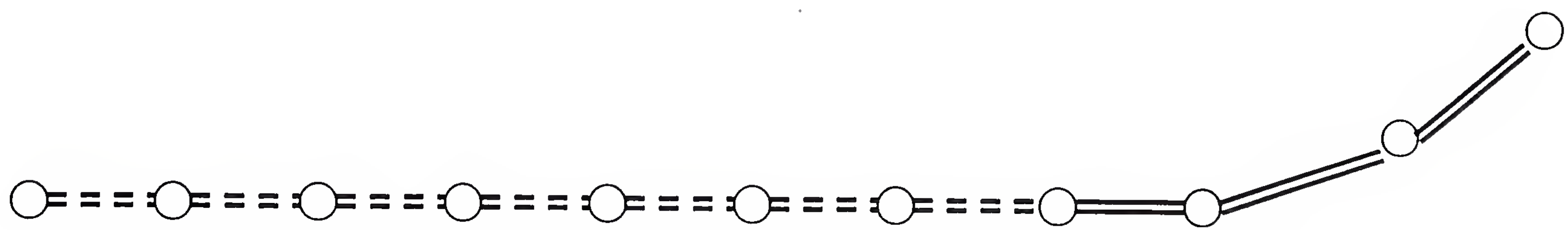


Figure 5.13: Configuration of 2 Beats in Design 3a

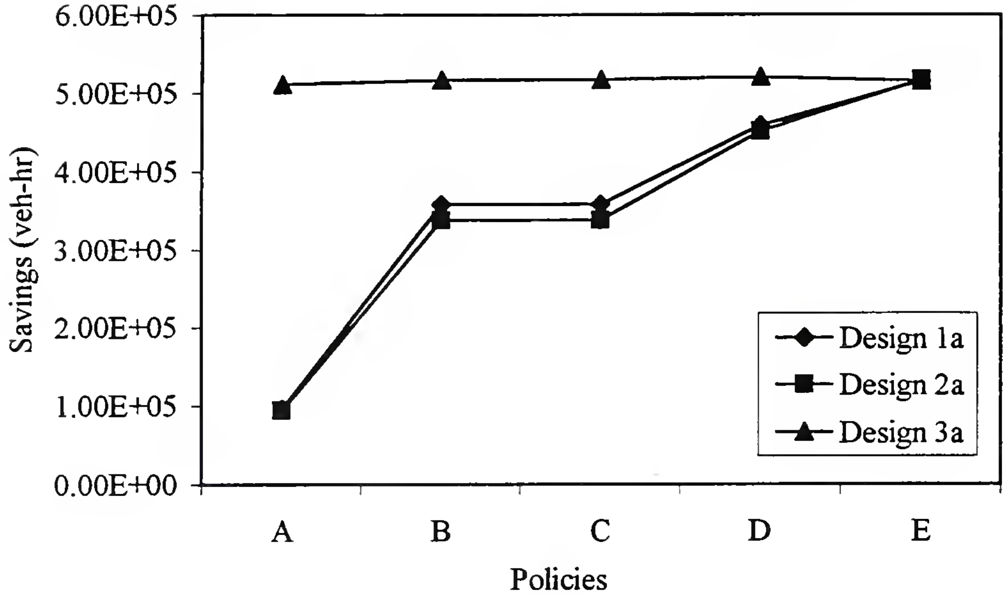


Figure 5.14: Savings in Total Vehicle-Hours in 200 Days due to Incident Response Operation (2 Beats in the Off-Peak Period and I-65 is Not Included)

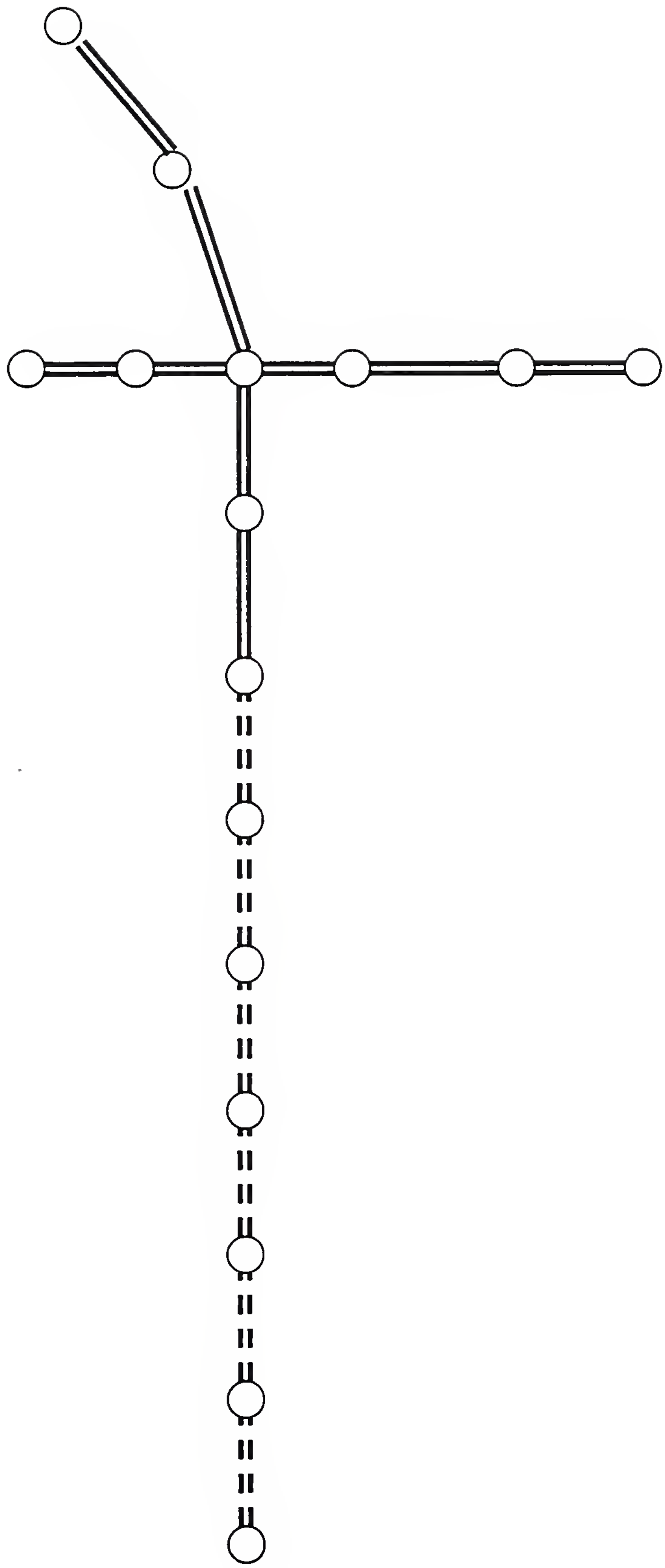


Figure 5.15: Configuration of 2 Beats in Design 1b

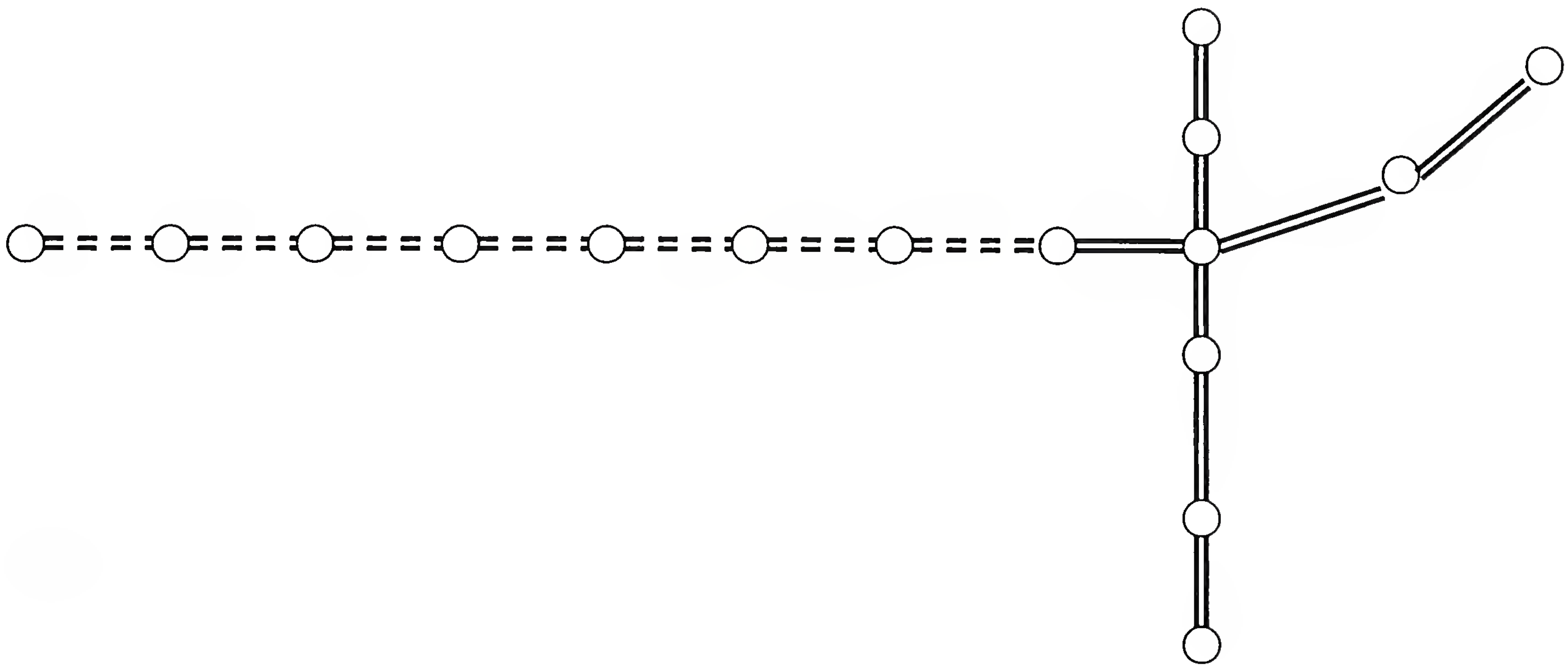


Figure 5.16: Configuration of 2 Beats in Design 2b

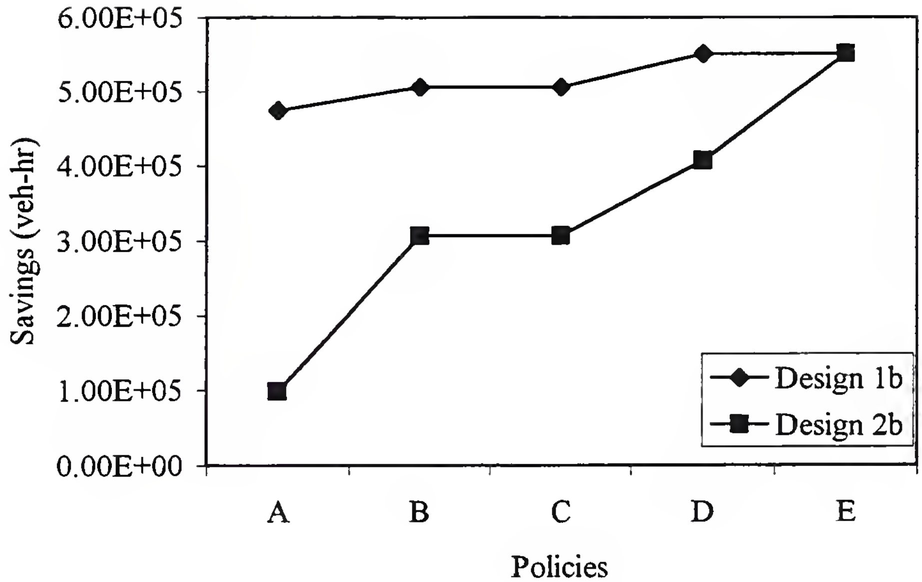


Figure 5.17: Savings in Total Vehicle-Hours in 200 Days due to Incident Response Operation (2 Beats in the Off-Peak Period and I-65 is Included)

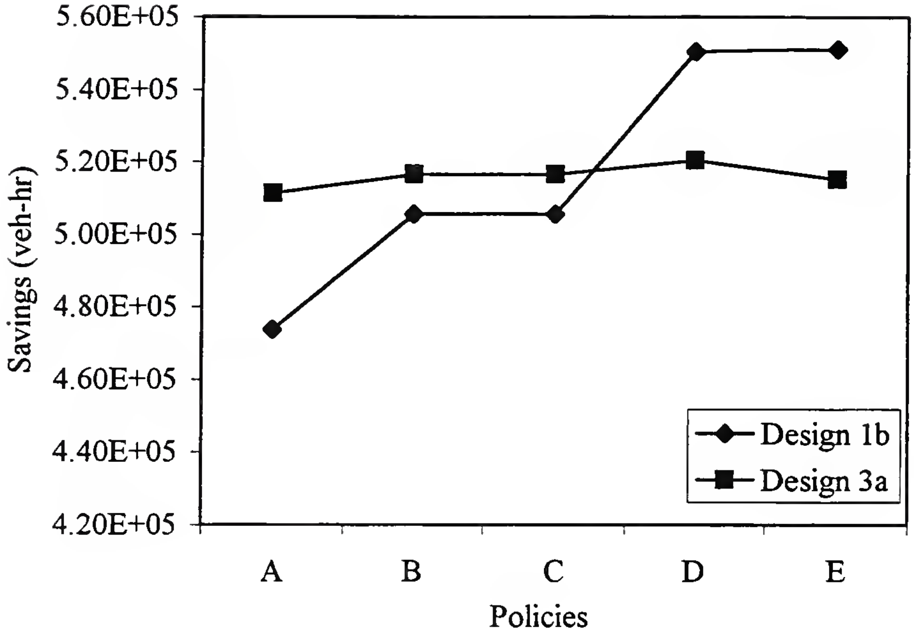


Figure 5.18: Savings in Total Vehicle-Hours in 200 Days due to Incident Response Operation in the Off-Peak Period
(I-65 is Included in Design 1b and I-65 is Not Included in Design 3a)

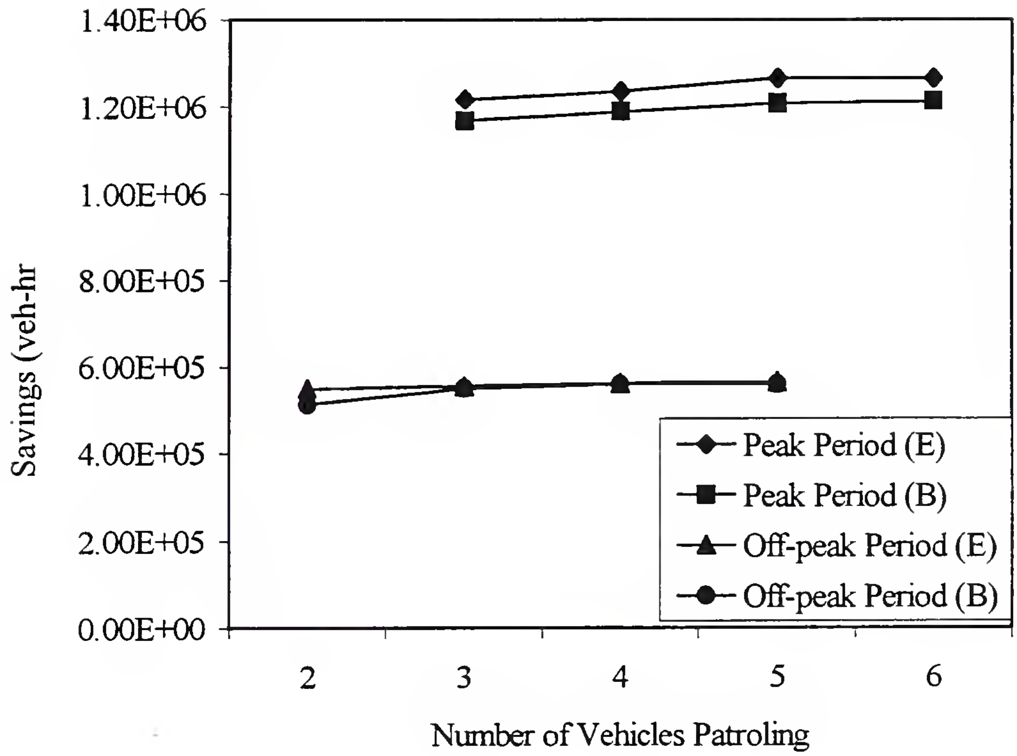


Figure 5.19: Savings in Total Vehicle-Hours in 200 Days due to Incident Response Operation in the Peak and Off-Peak Periods

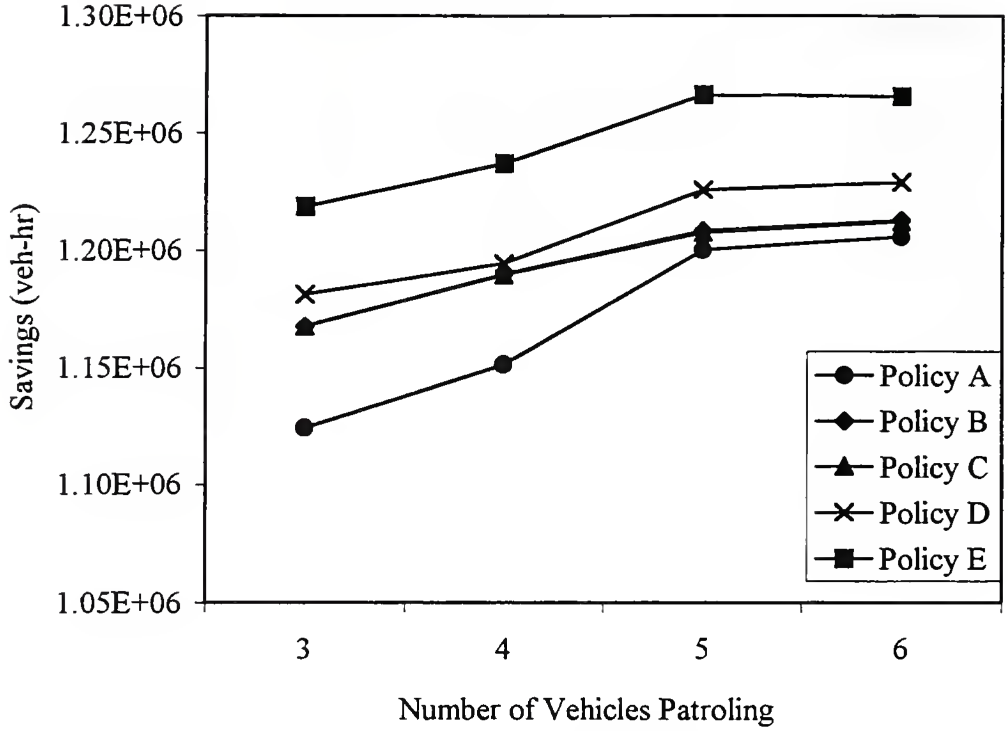


Figure 5.20: Savings in Total Vehicle-Hours in 200 Days due to Incident Response Operation by Varying Number of Vehicles in the Peak Period

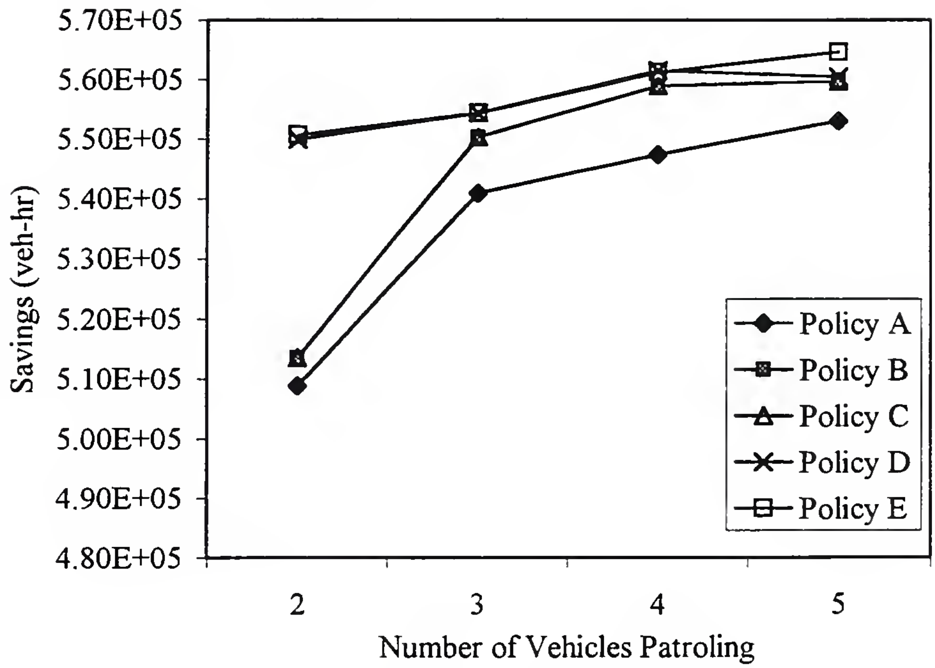
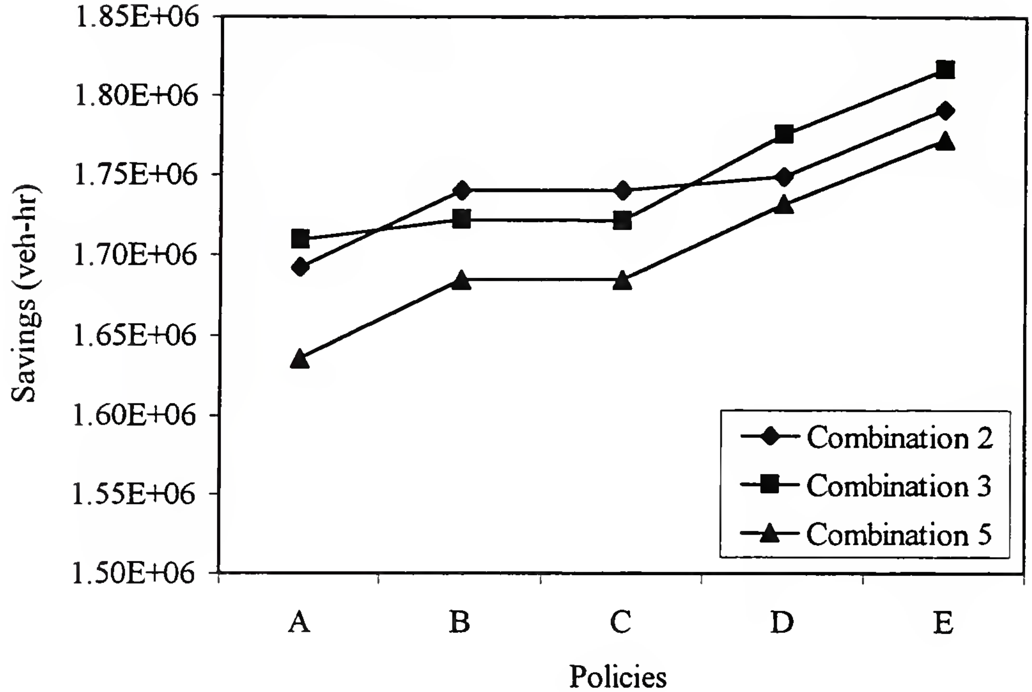


Figure 5.21: Savings in Total Vehicle-Hours in 200 Days due to Incident Response Operation by Varying Number of Vehicles in the Off-Peak Period



Note:
Combination 2: 4 vehicles in the peak period and 3 vehicles in the off-peak period
Combination 3: 5 vehicles in the peak period and 2 vehicles in the off-peak period
Combination 5: 3 vehicles in the peak period, 2 vehicles in the off-peak period, and 2 vehicles at night

Figure 5.22: Savings in Total Vehicle-Hours in 200 Days due to Incident Response Operation under Different Combinations of Hours of Operation (Fleet Size = 7)

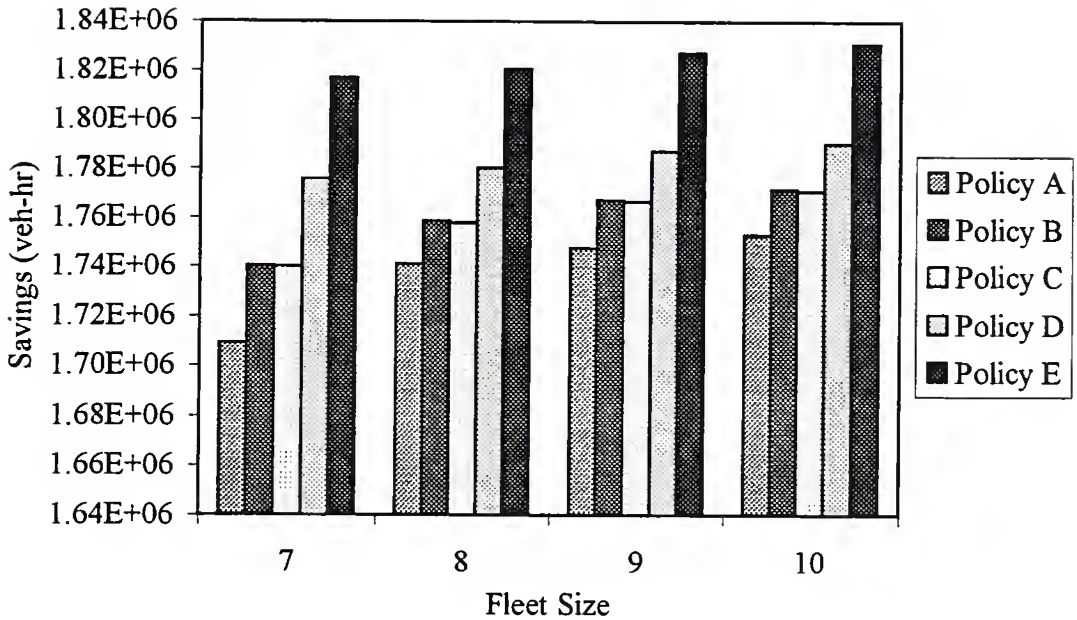


Figure 5.23: Savings in Total Vehicle-Hours in 200 Days under Different Dispatching Policies

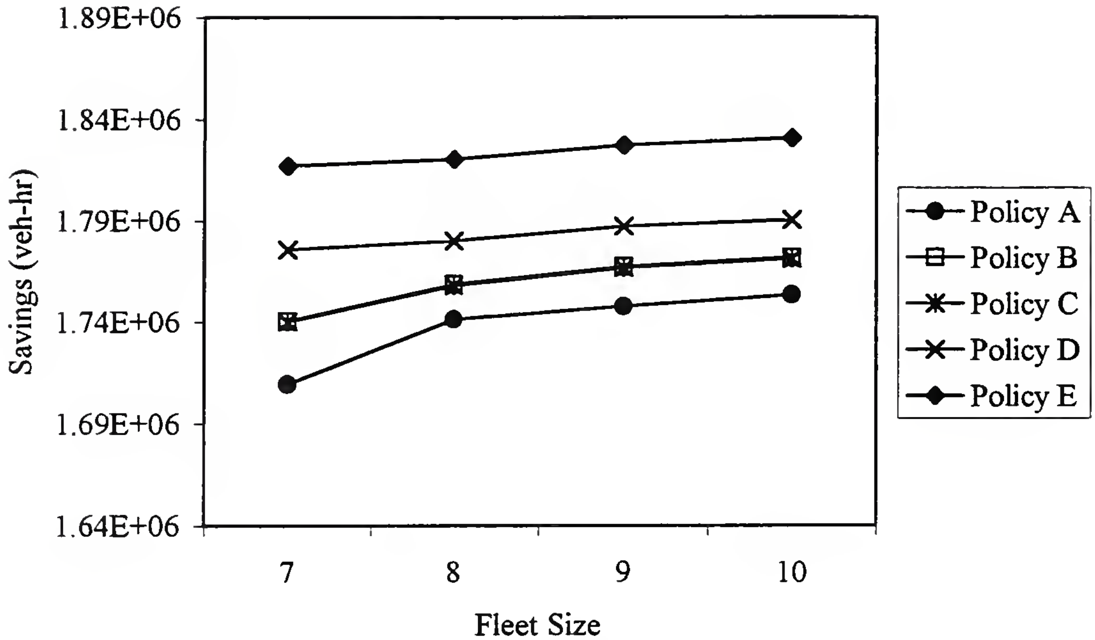


Figure 5.24: Effect of Fleet Size on Savings in Total Vehicle-Hours (in 200 days)

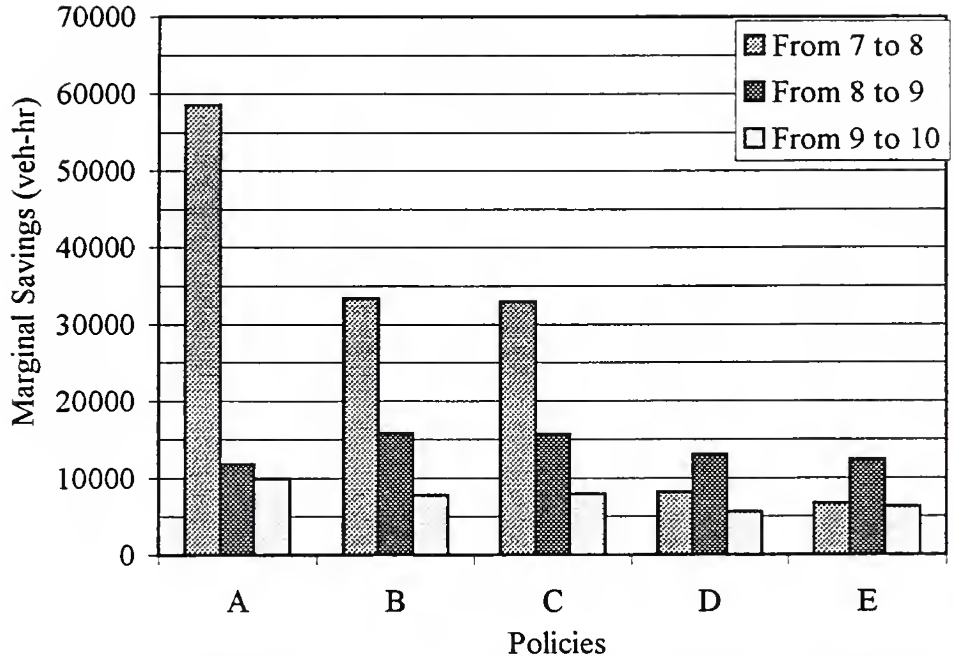


Figure 5.25: Expected Increase in Savings in Total Vehicle-Hours in One Year by Increasing the Fleet Size

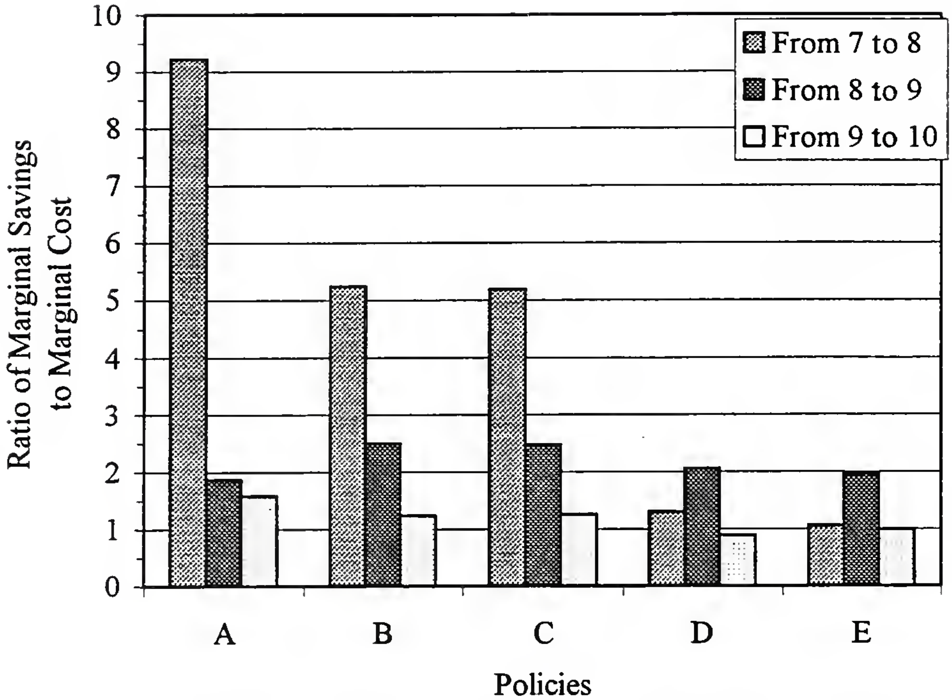
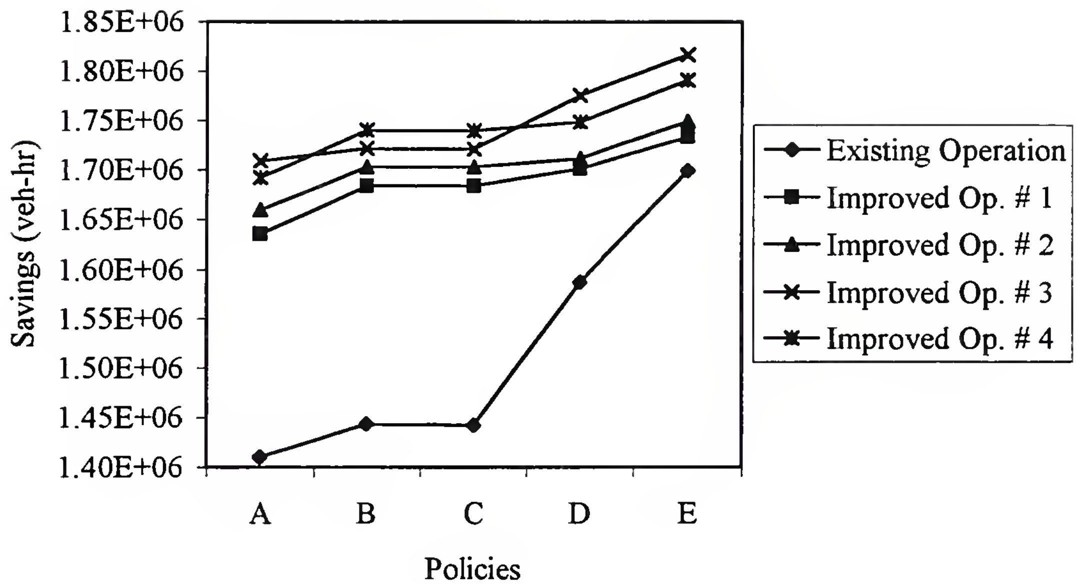


Figure 5.26: Effect of Increasing Fleet Size on Marginal Benefit-Cost Ratio



Note:
Existing Operation: 3 vehicles in the peak period, 2 vehicles in the off-peak period, and 2 vehicles at night
Improved Operation # 1: Same hours of operation as the existing operation, different beat design
Improved Operation # 2: 4 vehicles in the peak period, 2 vehicles in the off-peak period, and 1 vehicle at night
Improved Operation # 3: 5 vehicles in the peak period and 2 vehicles in the off-peak period
Improved Operation # 4: 4 vehicles in the peak period and 3 vehicles in the off-peak period

Figure 5.27: Comparison of Savings in 200 Days under Existing Operation and Improved Operation

CHAPTER 6

CONCLUSION

6.1 Summary of Findings

The study investigated the problem of optimal design of freeway incident response systems. A modeling framework was developed based on dynamic simulation and heuristic optimization techniques. As an example application of the proposed methodology, the case of the Hoosier Helper patrol program in northwest Indiana was considered. It was found that each of the system parameters, including fleet size, deployment schedule, area of operation, dispatching policy, and routing scheme, plays a major role in efficient operation of the response program. Dispatching policies that depend on automatic detection indicated much higher system benefits than policies based on visual detection by roving patrol vehicles. Automatic detection can also make it possible to cover a larger area of operation with the same fleet and crew sizes. The efficiency of the incident response program can also be improved by systematically determining the deployment schedule (hours of operation) and routing scheme (beat design) while keeping the fleet size the same. As one may intuitively perceive, the performance of the incident response operation varies with the number of response vehicles. The larger the fleet size is, the smaller the beat size and the quicker the incident detection and response, resulting in better performance. However, it may not be always cost-effective to increase the fleet size. While a larger fleet size adds benefit by increasing savings in total vehicle-hours in the system, it also adds cost. A trade-off analysis is recommended to determine desirable fleet sizes on the basis of marginal benefit-cost ratios.

6.2 Scope for Implementation

The methodology developed in this study is a generalized framework. The case of the Hoosier Helper program on the Borman Expressway was examined as an example application of the proposed methodology. However, the methodology is transferable and it can be applied to any other similar freeway patrol programs in Indiana or elsewhere. In order to use it for designing a new program or improving the operation of an existing program, the necessary input data would include incidents, traffic, and the study area network geometric features. The simulation model should also be calibrated accordingly. For marginal benefit-cost analysis it would be necessary to have data on the dollar value of a vehicle-hour saved and the system cost data including investment cost, overhead cost, maintenance cost, and employees' salaries and benefits.

6.3 Contribution of the Research

Not much information is currently available on the problem of optimal incident response system design. The present research is intended to fill this gap by investigating the impact of different system parameters on the effectiveness of an incident response system. The parameters considered included fleet size, deployment schedule, area of operation, dispatching policy, and routing scheme. Unlike previous studies, the focus of the present research was to optimize a direct system performance measure such as total vehicle-hours in the system, rather than minimizing indirect measures like mean response time of a vehicle or mean waiting time of incidents. The goal of an incident response program is to reduce the adverse effect of incidents on traffic as much as possible. Hence, it is desirable to use a performance measure like total vehicle-hours in the system that would directly incorporate the influence of incidents on traffic. A simulation model was developed to capture dynamically the adverse effects of incidents on traffic, including route diversion, reduction in speed, and delay in a queue. The study replicated the operation of roving freeway service patrol vehicles that move through time-varying traffic and undertake the joint responsibilities of incident detection and response. The role of different probable dispatching policies under visual detection, as well as automatic detection, was also extensively studied. Optimization techniques such as the nested partitions method and a load balancing algorithm were combined with the simulation model to develop desirable system designs that can improve the efficiency of an incident response program.

6.4 Future Research Directions

The present research proposed a framework that would assist transportation agencies to design new incident response programs as well as improve existing programs. The goal was to develop a comprehensive tool that can be used to determine the optimal system parameters including fleet size, deployment schedule, area of operation, dispatching policy, and routing scheme. The framework developed in the present study is intended for use in long term planning. Further research can consider planning for unusual events. For example, deployment schedules, as well as beat designs for response vehicles, can be altered in the event of major short term changes in the system caused by temporary closures of certain links due to severe crashes or by a large increase in traffic volumes due to sporting or other events. Another area of further research is to study how real time data can be used to modify design parameters adaptively so that the effectiveness of the program can be enhanced further.

The present research indicated that a wider area can be covered when more information about incidents is available through automatic detection. Furthermore, the use of automatic detection can reduce the number of response vehicles required. Further research can be undertaken to evaluate the cost-effectiveness of installing various automatic incident detection systems with respect to incident response.

In the present study, the nested partitions method used a one-dimensional search to find the optimal beat design while keeping other parameters fixed at a time. The approach can be extended to a multi-dimensional search that could generate optimal solutions for combinations of system parameters. Such a scheme would be worthwhile for designing a large incident response system, in which case it may be difficult to keep track of all different combinations of parameters that are kept fixed at a time. However, a multi-dimensional search may face difficulties as the size of the solution space would increase tremendously as various parameters are considered all together. Moreover, the partitioning of the solution space would be greatly complicated as more than one dimension is involved. As a number of solutions are sampled from the solution space at a time in the nested partitions method, computational time may be saved if these solutions are evaluated simultaneously, possibly using distributed computing. In fact, an important extension of the present research can be to investigate how a multi-dimensional search may be implemented using distributed computation.

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APPENDICES

APPENDIX A

COMPUTER PROGRAM FOR GENERATING INCIDENTS

Introduction

This program (incgen.c) is for generating incidents in a given study area. The study area may be defined by providing the information about the links. The historical incident data for the study area should be collected and analyzed to obtain the input data needed in the program. The input data needed is described in details in the subsequent sections. Incidents are generated according to a non-homogeneous/time-varying Poisson process. The average hourly incident rate is used to generate incidents in each hour. Poisson distribution, where the mean is the average hourly incident rate, is used to determine the number of incidents occurring in each hour. For each hour, probability values for occurrence of different types of incidents are calculated from the collected incident data. A random number is generated from a uniform distribution with range of 0 to 1 that is subsequently used to determine the incident type depending on the cumulative probability values for occurrence of different types of incidents. Distributions like exponential, gamma, log-normal, triangular, uniform, and Weibull can be fitted depending on type, location, and time of occurrence of incident to randomly generate incident clearance time.

Customization of the Program

A number of variables are defined at the top of the program. These may be altered to customize the program for a given study area. These variables are as follows:

no_of_link : It indicates the total number of links on which incidents will be generated. It should be defined one higher than the actual number of links. For example, if it is sought to generate incidents on 10 links, no_of_link should be specified as 11.

no_of_intv : The probability of occurrence of a particular type of incident, its lateral and longitudinal location, as well as clearance time depends on the time of incident occurrence. In order to capture this temporal effect the whole day be divided into a number of intervals (no_of_intv). The user may adjust this number according to his desired level of accuracy as well as data availability. Again, it should be defined one higher than the actual number of intervals.

Other Relevant Information

The other important variables are:

no_of_inc_type : The number of incident types should be specified one higher than the actual number. Four types of incidents (such as crash, abandoned vehicles, debris, and disablement) are considered. Hence, no_of_inc_type is specified as 5 in the program.

no_of_blck_type : The number of blockage types should be specified one higher than the actual number. Two types of blockage (such as lane and shoulder) are considered here. Hence, no_of_blck_type is specified as 3 in the program.

The number of days for which incidents have to be generated can be input interactively from the computer screen. Similarly, the initial seed (preferably a nine digit number) for random number generation should be specified.

Input Files

Seven input files are used in the program for incident generation. The information in these files has to be updated to customize it for a given study area.

File : problink1.data

There should be (no_of_intv – 1)*(no_of_link – 1) rows of data in this file. Each row has three entries. They are as follows:

1st entry : interval number

2nd entry : link number

3rd entry : probability that the incident is on a particular link given that it occurred in a particular time interval. It should be noted that, for a given time interval, the sum of these probability values over all links should be one.

File : clrtm1.data

This file contains data regarding clearance time of incident. There should be (no_of_inc_type –1)*(no_of_blck_type – 1)*(no_of_intv – 1) rows of data in this file. Each row has eight entries. They are as follows:

1st entry : type of incident. Type

1 for crash

2 for abandoned vehicle

3 for debris

4 for disablement

2nd entry : type of blockage. Type

1 for lane

2 for shoulder

3rd entry : interval number (type a number : 1, 2, 3, 4, 5, 6 ... depending on interval number)

4th entry : type of fitted distribution. Type

1 for exponential

2 for gamma

3 for Weibull

4 for log-normal

5 for triangular

6 for uniform

5th entry : intercept. It is the shift parameter (in minutes) that is added to the clearance time generated from fitted distributions.

6th entry : 1st parameter

Exponential : lambda (mean)

Gamma : alpha (shape parameter)

Weibull : alpha (shape parameter)

Log-normal : mu (mean)

Triangular : a (minimum value)

Uniform : a (lower limit)

7th entry : 2nd parameter

Exponential : not needed to specify the distribution, type 0.

Gamma : beta (scale parameter)

Weibull : beta (scale parameter)

Log-normal : std (standard deviation)

Triangular : b (maximum value)

Uniform : b (higher limit)

8th entry : 2nd parameter

Exponential : not needed to specify the distribution, type 0.

Gamma : not needed to specify the distribution, type 0.

Weibull : not needed to specify the distribution, type 0.

Log-normal : not needed to specify the distribution, type 0.

Triangular : c (mode, i.e. the number that occurs most frequently)

Uniform : not needed to specify the distribution, type 0.

File : probinc1.data

This file contains data regarding probability of occurrence of different types of incidents. There should be (no_of_link –1)*(no_of_intv – 1) rows of data in this file. Each row has five entries. They are as follows:

1st entry : link number

2nd entry : interval number

3rd entry : probability that an incident on a given link in a given time interval is a crash

4th entry : probability that an incident on a given link in a given time interval is an abandoned vehicle

5th entry : probability that an incident on a given link in a given time interval is debris

File : probblck1.data

There should be (no_of_inc_type –1) rows of data in this file. Each row has two entries. They are as follows:

1st entry : type of incident. Type

1 for crash

2 for abandoned vehicle

3 for debris

4 for disablement

2nd entry : probability that an incident is on a lane given the type of incident

File : boundary1.data

There should be (no_of_intv –1) rows of data in this file. Each row has three entries. They are as follows:

1st entry : interval number

2nd entry : time (in hour) when the particular time interval starts

3rd entry : time (in hour) when the particular time interval ends

File : link11.data

This file contains information regarding the links on which incidents will be generated. There should be (no_of_link –1) rows of data in this file. Each row has four entries. They are as follows:

1st entry : link number

2nd entry : length of the link

3rd entry : node from which the link starts (interchange where travel on the link begins)

4th entry : node at which the link ends (interchange where travel on the link ends)

File : rate1.data

This file contains information regarding hourly incident occurrence rate. There should be 26 rows of data in this file. Each row has two entries. They are as follows:

1st entry : integers from 0 to 25

2nd entry : incident occurrence rate per hour. It should be noted that

rate[1] = incident occurrence rate in 1st hour (Midnight – 1AM)

rate[24] = incident occurrence rate in 24th hour (11PM - Midnight)

rate[0] = rate[1]

rate[25] = rate[24]

<u>Output Files</u>

There are three output files where the information of the incidents generated by the program is stored. They are as follows:

File : output1.info

Each row gives information regarding a particular incident. There are nine entries in each row. They are as follows:

1st entry : day of occurrence

2nd entry : time of the day

3rd entry : link on which the incident occurs

4th entry : node from which the link starts (interchange where travel on the link begins)

5th entry : node at which the link ends (interchange where travel on the link ends)

6th entry : distance (in miles) from the node at which the link starts (interchange where travel on the link begins)

7th entry : type of incident. The file prints

1 for crash

2 for abandoned vehicle

3 for debris

4 for disablement

8th entry : lateral location of incident. The file prints

1 for lane

2 for shoulder

9th entry : incident clearance time (in minutes)

File : output2.info

This file stores the total number of incidents occurring during the specified period.

File : output3.info

This file stores the number of incidents occurring in each hour of the day for the specified duration. There are twenty-four entries in this file.

APPENDIX B

COMPUTER PROGRAM FOR FORMATTING INCIDENT DATA AND CALCULATING LOADS

Introduction

This program (gen_loadcal.c) is used for calculating loads on the links in a given study area. The load on a link may be defined as the sum of clearance time of all the incidents occurring on it during a specified period. The load data (stored in file load.data) obtained is used in a load balancing algorithm. This program is also used to format the incident data generated from incident generation program (gigm.c). The formatted incident data (stored in files incident.data and noincsp.data) is subsequently used in the simulation programs for incident response operation.

Input Files

There are three input files. They are as follows:

File : output1.info

It is obtained from the incident generation program (gigm.c). For detailed description, the manual on incident generation program may be referred.

File : output2.info

It is obtained from the incident generation program (gigm.c). For detailed description, the manual on incident generation program may be referred.

File : spperiod.data

One may be interested to study the impact of incidents occurring only in certain periods of a day. These periods should be specified by defining the starting and ending time. In the program, there is provision of specifying up to two periods. If there is a need for specifying more than two periods, the program has to be modified. There are four entries in this file. They are as follows:

1st entry : time (in hours) when the first period starts

2nd entry : time (in hours) when the first period ends

3rd entry : time (in hours) when the second period starts

4th entry : time (in hours) when the second period ends

If the second period is not needed, 0 should be typed for 3rd and 4th entries.

Output Files

There are three output files. They are as follows:

File : incident.data

This contains the formatted incident data. Each row has eight entries. They are as follows:

1st entry : time of incident occurrence (in seconds from the start of the clock)

2nd entry : clearance time of incident (in seconds)

3rd entry : link on which the incident occurs

4th entry : node from which the link starts (interchange where travel on the link begins)

5th entry : node at which the link ends (interchange where travel on the link ends)

6th entry : distance (in miles) from the node at which the link starts (interchange where travel on the link begins)

7th entry : lateral location of incident. The file prints

1 for lane

2 for shoulder

8th entry : type of incident. The file prints

1 for crash

2 for abandoned vehicle

3 for debris

4 for disablement

File : noincsp.data

This file stores the total number of incidents occurring during the period specified in the file spperiod.data.

File : load.data

This file contains the information regarding calculated load (in minutes) on each of the links on which incidents are generated.

APPENDIX C

COMPUTER PROGRAMS FOR SIMULATION OF INCIDENT RESPONSE OPERATION

Introduction

These programs are used to replicate operation of the incident response vehicles that are moving through freeway traffic. Aggregate route diversion models are used along with queueing models to capture the non-linear impact of incidents on time-varying traffic. Five computers programs are developed to implement five different dispatching policies. They are as follows:

- Policy A : First Reached First Served without Crossing to the Other side (Computer Program : pla.c)
- Policy B : First Reached First Served with Crossing to the Other side (Computer Program : plb.c)
- Policy C : Most Severe First (Computer Program : plc.c)
- Policy D : Most Severe with Minimum Time to Respond First with Vehicle Patrolling (Computer Program : pld.c)
- Policy E : Most Severe with Minimum Time to Respond First with Vehicle Waiting on Shoulder (Computer Program : ple.c)

The detailed description of these policies can be found in Chapter 3 of the report. In addition to these five computer programs, another program, noir.c was developed to estimate system performance measures in absence of any incident response program.

Customization of the Programs

A number of array sizes are already defined in these programs so that they can be used for a fairly large problem. However, if the situation demands a user can increase the array sizes to handle a larger problem. The guidelines for specifying array sizes are given below:

ngbr[ ] : The array size should be at least one higher than the number of neighboring links on which traffic volume is affected due to route diversion. For a better understanding the network presented in Figure C.1 may be referred. It is assumed that diverted traffic from the freeway would return to the freeway within two blocks after bypassing the incident. Suppose there is an incident on the freeway on link 1. The diverted traffic would re-enter the freeway through links 23, 26, 27, and 30. The links, on which traffic volume is affected due to route diversion because of an incident on link 1, are 20, 13, 23, 15, 27, 21, 7, 26, 9, 30, 1, and 3. Hence the number of neighboring links for link 1 is 12. It should be noted that the link itself is considered as a neighboring link.

link[ ] : The array size should be at least one higher than the number of links in the network.

linkdes[ ][ ] : The size of both dimensions in this array should be at least one higher than the number of nodes in the network.

inc[ ] : The array size should be at least one higher than the number of incidents that would be generated in the entire simulation period.

veh[ ] : The array size should be at least one higher than the number of response vehicles in the fleet.

veh_sch[ ][ ] : The first index should be 25. The second index should be at least one higher than the number of response vehicles in the fleet.

route[ ][ ][ ][ ] : The first index should be at least one higher than the number of routes (beats) followed by the response vehicles in the entire day. The second and third indices should be at least one higher than the number of nodes in the network. The fourth index should be 5.

rtmemory[ ][ ] : The first index should be at least one higher than the number of routes (beats) followed by the response vehicles in the entire day. The second index should be higher than 30.

severity[ ][ ] : The first index should be at least one higher than the number of types of incidents. The second index should be at least one higher than the number of possible lateral locations (lane/shoulder) of incidents.

chtm[ ][ ][ ] : All the three indices should be at least one higher than the number of nodes for which these data are entered.

spath[ ][ ] : Both the indices should be at least one higher than the number of nodes for which these data are entered.

The array sizes in the function, shrtpath( ), that is used to obtain the shortest path between two nodes, should be at least one higher than the number of nodes for which shortest paths are to be obtained.

Input Data

There are a number of input files that are needed in these computer programs. They are as follows:

File : link1.data

This file contains information about the links in the study area. At the beginning of the file, the number of links should be specified. For each link, a set of data should be provided. They are as follows:

1st entry : link number

2nd entry : length of the link

3rd entry : link type. Type

1 for two lane highway

2 for four lane highway

3 for four lane highway

4th entry : capacity of the link

5th entry : speed limit on the link

6th entry : free flow speed on the link

7th entry : number of neighboring links on which traffic volume is affected due to route diversion

8th entry : maximum of time lag for all neighboring links (in seconds). If there were a major incident on link 1, vehicles would try to divert using links 20 and 21, shown in Figure C.1. This extra traffic on links 20 and 21 would eventually reach links 13 and 7, respectively. It would take some time for this extra volume to reach links 7 and 13. There is a lag between the time when route diversion starts and the time when the effect of route diversion (change in volume level) is perceived on neighboring links. Time lag for a particular neighboring link can be estimated by adding the average travel times on the links that are to be covered to reach at the entry point of that link. For example, suppose traffic diverts using link 21 due to an incident on link 1. Diverted traffic would eventually reach link 26 after covering links 21 and 7. Suppose the average travel times on these two links are 200 and 250 seconds respectively. Then the time lag for link 26 would be 450 seconds.

In addition to these data, the following information about each of the neighboring links should be provided:

1st entry : neighboring link number

2nd entry : percentage of volume diverted to the neighboring link (express in fraction, in between 0 to 1). The percentage value can be calculated based on the relative capacities of the entry links at each node. For example, suppose traffic is diverted from link 1 due to a major incident. There are two possible entry links: link 20 and link 21. Suppose their capacities are 1200 and 1800 vehicles/hour, respectively. Hence, percentage values for links 20 and 21 would be 40% (0.40 = 1200/(1200+1800)) and 60% (0.60 = 1800/(1200+1800)), respectively. For link 1, this value would be –100% (-1.0). The negative sign is due to the fact that volume level on link 1 is reduced due to diversion. For link 7, this value would be the same as that of link 21, as all the diverted traffic on link 21 would go through link 7 as well. After traversing link 7, drivers have the option of going on either link 9 or on link 26. Again, the relative capacities of links 9 and 26 are used to spit the diverted traffic on link 7. Suppose the capacities of links 9 and 26 are

1200 and 1800 vehicles/hour, respectively. Hence, the percentage values on links 9 and 26 would be 24% (0.24 = 0.60*0.40) and 36% (0.60*0.60). The term, 0.60, comes from the percentage value of link 7. A portion of diverted traffic returns from the arterials to the freeway through links 23 and 26. If the percentage values for links 23 and 26 are 20% and 36% respectively, the percentage value for link 3 would be –44% (-0.44 = 0.20+0.36-1.00). The term, -1.00, comes from the percentage value of link 1.

3rd entry : time lag for the neighboring link. The concept of time lag has already been discussed earlier.

File : link2.data

This file contains information about the connectivity of the links. At the beginning of the file, the number of links in the network is specified. Subsequently, the following data are provided for each link:

1st entry : node from which the link starts (interchange where travel on the link begins)

2nd entry : node at which the link ends (interchange where travel on the link ends)

3rd entry : link number

File : link3.data

This file contains additional information only for the links on which the response vehicles patrol. At the beginning of the file, the number of links, on which the response vehicles patrol, is specified. Subsequently, the following data are provided for each of such links:

1st entry : link number

2nd entry : direction of travel on the link. Type

1 for eastbound travel

2 for westbound travel

3 for northbound travel

4 for southbound travel

3rd entry : index of the route (beat) on which the link is located

File : link4a.data

This file is used by the function, shrtpath( ), that is used to obtain the shortest path between two nodes. There are four entries in this file. They are as follows:

1st entry : This should be 1.

2nd entry : number of nodes for which shortest paths are to be obtained

3rd entry : same as the 2nd entry

4th entry : number of links connecting the nodes for which shortest paths are to be obtained

File : link4b1.data

This file is also used by the function, shrtpath( ), that is used to obtain the shortest path between two nodes. The number of rows of data to be entered is same as the number of links specified in the 4th entry of the file, link4a.data. For each links the following information should be provided:

1st entry : node from which the link starts (interchange where travel on the link begins)

2nd entry : node at which the link ends (interchange where travel on the link ends)

3rd entry : link number

4th entry : average travel time (in seconds) on the link

File : vol.data

This file contains information about hourly volumes on the links in the network. At the beginning of the file, the number of links in the network is specified. Subsequently, the link number and its hourly volume for each hour of the 24-hour period in day are provided for each link:

File : noincsp.data

This file contains information about the total number of incidents occurring in the study area during a specified period. This file is generated from the program, gen_loadcal.c, that is used to format the incident data generated from an incident generation model.

File : incident.data

This file contains information about the individual incidents occurring in the study area during a specified period. This file is also generated from the program, gen_loadcal.c, that is used to format the incident data generated from an incident generation model.

File : veh.data

This file contains information about the response vehicles. At the beginning of the file the following information is provided:

number of vehicles : number of response vehicles in the fleet

sight distance : distance (in miles) within which an incident can be detected by the response vehicle

depot node : the location where the response vehicles return after finishing their patrol and response duties in the scheduled period operation. It should to be specified as a node in the network.

number of vehicle schedule entries : For each of the 24-hour period, data should be entered in separate rows for each of the vehicles operating in that hour. For example, if 3 vehicles are patrolling in the 1st hour of the day, then number of rows of data to be entered for that hour is 3. The total number of such rows for the entire day is equal to the number of vehicle schedule entries.

Each row has five entries. They are as follows:

1st entry : index of the hour

2nd entry : index of the vehicle

3rd entry : index of the route (beat) in which the vehicle is patrolling

4th entry : need status. Type 1 for this entry. It indicates that there is a need for this vehicle in this hour.

5th entry : time of the day (in seconds) when the vehicle starts to move to the depot after finishing its duties in the scheduled hour of operation

Route Data

The data about the routes are provided in three files. They are as follows:

<u>File : rtreg.data</u>

This file contains information about the routes that are followed by a response vehicle routinely while it is patrolling the freeway. At the beginning of the file, the number of rows of entries should be specified. For each link two rows of data are entered, one with the direction of travel same as that of the link, and the other with the direction of travel opposite to that of the link. Hence, the number of rows would be 2*(number of links in all the routes). The links to be covered by a response vehicle for coming from the depot node to the patrol area as well as for returning to the depot from the patrol area also should be included. For example, suppose one vehicle covers links 1 through 6, as shown in Figure C.1. It comes to its patrol area from a depot, located at the junction of links 9, 12, and 29. Hence, the vehicle has to cover links 29 and 30 in addition to six links in its patrol area. Thus, for this one-vehicle case, the number of rows of data to be entered would be 16 (16 = 2*(6+2)).

A decision is made at each node regarding the next node to go to. This decision is dependent on the node from which the vehicle is coming as well as its direction of travel. The entries in each row are as follows:

1st entry : index of the route

2nd entry : node at which decision is made

3rd entry : node from which the vehicle is coming

4th entry : direction of travel. Type

1 for eastbound direction

2 for westbound direction

3 for northbound direction

4 for southbound direction

5th entry : the next node the vehicle would go

6th entry : primary direction of travel when the vehicle would go to the next node. In this file the 6th entry remains the same as the 4th entry for all links in the patrol area unless it is turning around in the loop. If it turns around the new direction of travel should be entered as the 6th entry. For the links that are not in the patrol area but are to be covered for access to the depot, the 6th entry would be the direction of travel the vehicle has to follow to go to the next node while coming from the depot to the patrol area.

7th entry : change time. When the vehicle moves from one link to another, it may take some extra time. If it is going straight it does not take extra time (type 0.0 for this case), but if it is turning it takes some extra time depending on left or right turns. The extra time (in seconds) should be entered as an input data.

File : rtdiv.data

This file contains information about the routes that are followed by a response vehicle when it turns around at the nearest exit to attend an incident on the other side of the freeway with opposite direction of travel.

At the beginning of the file, the number of rows of entries should be specified. For each link two rows of data are entered, one with the direction of travel same as that of the link, and the other with the direction of travel opposite to that of the link. Hence, the number of rows would be 2*(number of links in all the routes).

A decision is made at each node regarding the next node to go to. This decision is dependent on the node from which the vehicle is coming as well as its direction of travel. The first four entries in each row are the same as that of rtreg.data. However, the 5th entry (next node to go to) would be different from that in rtreg.data, as the vehicle needs to turn around to attend an incident on the other side of the freeway. In this file the 6th entry (primary direction of travel when the vehicle would go to the next node) remains the same as the 4th entry for all links in the patrol area. For the links that are not in the patrol area but are to be covered for access to the depot, the 6th entry would be the direction of travel the vehicle has to follow to go to the next node while coming from the depot to the patrol area. The 7th entry (change time) should be adjusted accordingly.

File : rtret.data

This file contains information about the routes that are followed by a response vehicle when it starts returning to the depot after finishing its patrol and response duties in the scheduled period of operation.

At the beginning of the file, the number of rows of entries should be specified. For each link two rows of data are entered, one with the direction of travel same as that of the link, and the other with the direction of travel opposite to that of the link. Hence, the number of rows would be 2*(number of links in all the routes).

A decision is made at each node regarding the next node to go to. This decision is dependent on the node from which the vehicle is coming as well as its direction of travel.

The first four entries in each row are the same as that of rtreg.data. However, the 5th entry (next node to go to) would be different from that in rtreg.data, as the vehicle is returning to the depot and hence would not turn around to attend an incident on the other side of the freeway or to cover the patrol area. In this file the 6th entry (primary direction of travel when the vehicle would go to the next node) for all links would be the direction of travel the vehicle has to follow to go to the next node while returning to the depot from the patrol area. The 7th entry (change time) should be adjusted accordingly.

File : rtmem.data

The array, rtmemory[ ][ ], is used to store information about incident's detection and response. The first index in the array indicates the route number and the second one indicates the incident index stored in the array. The file, rtmem.data, specifies the size of this array.

File : sever.data

This file contains information of severity of incident depending on type (crash, abandoned vehicle, debris, and disablement) and lateral location (lane and shoulder). At the beginning of the file, the total number of rows of data to be entered is specified. This number would be (number of types)*(number of lateral locations). For each row, the following data are entered:

1st entry : type of incident

2nd entry : lateral location of incident

3rd entry : severity ranking of incident. Assign the value 1 for the most severe incident, 2 for next severe incident, and increase the value as the severity level goes down.

File : chng.data

This file contains information regarding extra time needed to move from one link to another. At the beginning of the file, the total number of rows of data to be entered is specified. For each row, the following data are entered:

1st entry : node from where the vehicle is coming from

2nd entry : the node where the vehicle is at now

3rd entry : the node where the vehicle will be going next

4th entry : change time. When the vehicle moves from one node to another, it may take some extra time. If it is going straight it does not take extra time (type 0.0 for this case), but if it is turning it takes some extra time depending on left or right turns. The extra time (in seconds) should be entered as an input data.

File : invhpsn.data

This file contains information regarding the initial position of all the response vehicles. Initially, all of them are located the depot. At the beginning of the file, the total number of rows of data to be entered is specified. It would be the same as the number of vehicles. For each vehicle, the following data are entered:

1st entry : vehicle index number

2nd entry : depot node

3rd entry : node at which the link connecting the depot to the network ends. In case the depot is connected to more than one link, choose the one that would minimize the travel time to the patrol area.

4th entry : distance from depot. Type 0.0 for this entry.

5th entry : direction of travel on the link connecting the depot to the network. Type

1 for eastbound direction

2 for westbound direction

3 for northbound direction

4 for southbound direction

File : tempdepot.data

If policy E is implemented, the response vehicle waits on the shoulder at a location that is more or less center of the beat. This location can be referred to as a temporary depot. This file contains information about such temporary depots. The link on which a temporary depot is located is referred to as a temporary depot link. At the beginning of the file, the total number of rows of data to be entered is specified. It would be the same as the number of vehicles. For each vehicle, the following data are entered:

1st entry : vehicle index number

2nd entry : node where the temporary depot link starts

3rd entry : node where the temporary depot link ends

4th entry : distance of the temporary depot from the starting node of the temporary depot link

5th entry : direction of travel on the temporary depot link. Type

1 for eastbound direction

2 for westbound direction

3 for northbound direction

4 for southbound direction

Simulation Parameters

The simulation parameters are specified from the screen. They are as follows:

simulation period : number of days for which simulation would be run

simulation interval : interval (in seconds) at which all variables would be updated

Output

The system performance can be measured in terms to total time spent by the vehicles in the network when they move as well as spend time in queues. The delay in queue can also be estimated separately. This information is printed on the screen as well as is stored in files specified by the pointers infovehhr and infodelay, respectively. There is also a provision of creating a number of output files where other relevant information can be stored.

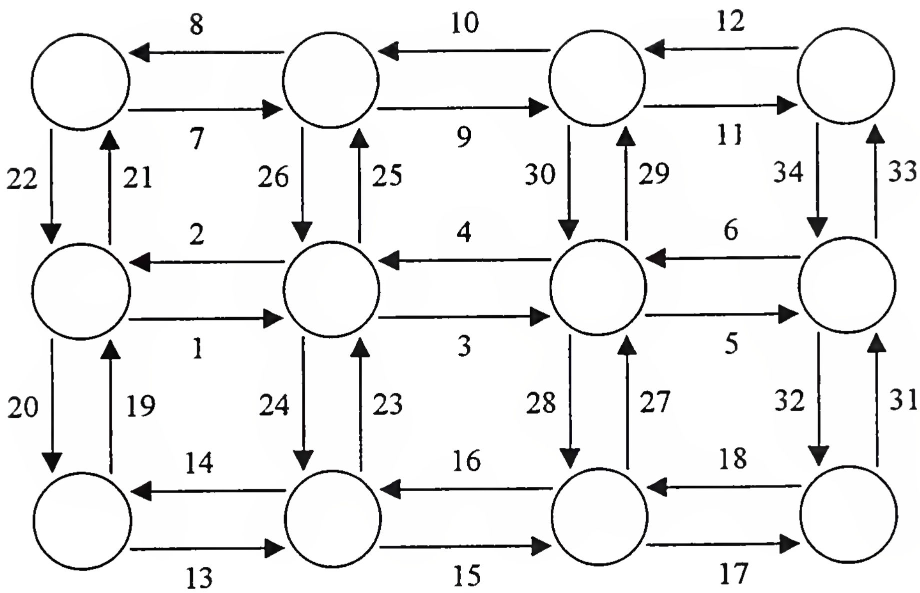

Figure C.1 : Example of a Study Network

APPENDIX D

COMPUTER PROGRAM FOR INITIAL BEAT DESIGNS

Introduction

A good beat design can be obtained by balancing the workload among the beats. Workload balancing ensures that all the response vehicles are kept more or less equally busy which in turn reduces the average response time to an incident. The idea is to divide the patrol area into a number of beats in such a way that minimizes the difference of workload among all the beats. The workload can be estimated by summing up the incident clearance time of all the incidents occurring on the freeway segments being covered by the patrol program, and a load balancing algorithm can be used to obtain the beat design. This program (part.c) is used for implementation of the load balancing algorithm. Heuristic techniques such as multiple leaf swap, branch swap, single leaf swap, and cycle swap are used for balancing loads.

Customization of the Program

A number of array sizes are already defined in the program that can tackle a fairly large size problem. However, array sizes may be modified to handle even a larger data set. The guidelines for specifying array size are given as follows:

link[ ] : The array size should be at least one higher than the number of links in the patrol area.

lnbr[ ] : The array size should be at least one higher than the maximum number of neighbors a link can have. The neighbors of a given link are the links that are adjacent to it and can be reached directly from it without traversing a second link. Figure D.1 can be referred for explanation. Link 1 has just one neighbor: link 3, link 2 does not have any neighbor, and link 3 has three neighbors: links 5, 7, and 9. It should be noted that paired links, which are the links between the same two nodes, are not treated as neighbors. For example, links 1 and 2 are paired links and link 1 is not a neighbor of link 2.

node[ ] : The array size should be at least one higher than the number of nodes in the study area.

partition[ ] : The array size should be at least one higher than the number of beats in which the patrol area has to be divided.

spath[ ][ ] : The size of both dimensions in this array should be at least one higher than the number of nodes in the study area.

Input Data

There are three input files. They are as follows:

File : network.data

The information about two variables is provided here:

no_of_node : number of nodes in the study network

no_of_link : number of links in the study network

File : netlink.data

For each link a set of data are to be entered. The entries are as follows:

1st entry : current link number

2nd entry : node from which the link starts (interchange where travel on the link begins)

3rd entry : node at which the link ends (interchange where travel on the link ends)

4th entry : index of the link that is the paired with the current link

5th entry : number of links that are neighbors to the current link

In the following lines, the indices of the neighboring links have to be entered.

File : load.data

This file contains the information regarding calculated load (in minutes) on each of the links on which incidents are generated. This file is created by the program for load calculation, gen_loadcal.c. It has no_of_link rows of data. Each row has two entries:

1st entry : link number

2nd entry : load on the link

Apart from these input files, a number of data have to be entered interactively from the computer screen. They are as follows:

- For allowable percentage of violation from the average workload of the partition, it is preferable to use a smaller value so that workloads are balanced as much as possible. 1 percent may be used as a recommended value.
- For unit price for violating upper bound on workload in a partition, a value of one may be used. It should be noted that smaller the value, more is the balance in workload among the beats.

- For unit price for violating lower bound on workload in a partition, a value of one may be used. It should be noted that smaller the value, more is the balance in workload among the beats.
- For number of partitions needed, type the number of beats among which the patrol area should be divided.

Output Data

A number of output data are printed on the screen. The most relevant outputs are printed towards the end. These are link numbers (k) and beats (link[k].final_part_index) they are assigned to. The other data gives information about degree of unbalance among the beats.

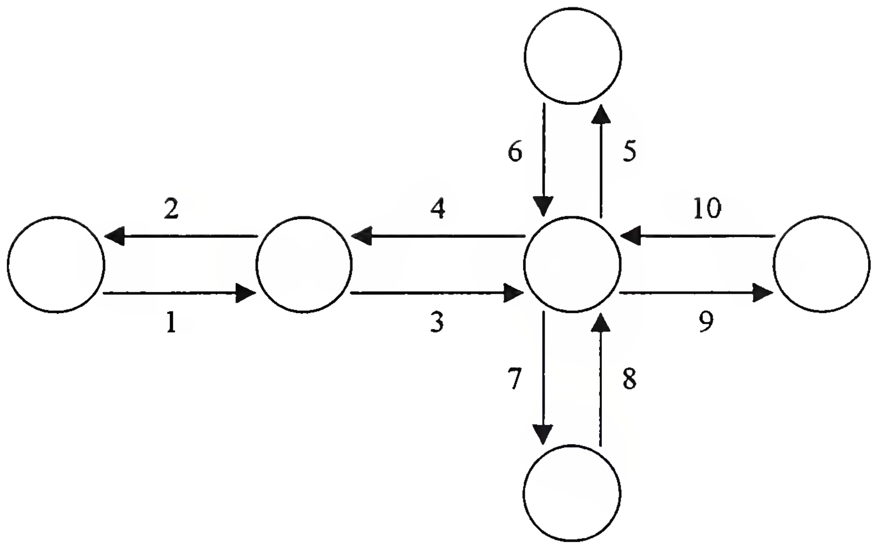

Figure D.1 : Example of a Study Network